Simulation the dynamics of hub-motors of an automatic guided vehicle in occurrence of planetary gear tooth defects

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Abstract. The article discusses the process of studying the dynamics of hub-motor control systems mounted in an automatic guided vehicle (AGV), in the presence of breakage of the teeth of the ring gear of the planetary mechanism using virtual prototyping technologies. A model of a two-loop pulse modulated control system for the angular velocity of the Green E-Motion hub-motors as part of an AGV with a differential drive implemented in Matlab Simulink, with the integration of the mechanical part of the virtual prototype built in MSC Adams is described. The defect and backlash in the planetary gearbox of the hub-motors were modelled using 3D contact forces. Experimental test setup for the hub-motor virtual prototype validating is presented. As a result of co-simulation, the features of the hub-motors dynamics during the rectilinear movement of AGV in the occurrence of planetary gear tooth defects are revealed.

1. Introduction

Automatic guided vehicles (AGV) are important elements in building flexible manufacturing, logistic and storage systems. One way to reduce their cost is to use inexpensive drive devices. At the same time, to ensure the survivability of the AGV in the on-board control systems, operation algorithms can be programmed in case of failure or breakdowns.

Recently, hub-motors or electric motors mounted in a wheel hub have been widely used as drive devices in AGV. A brushless direct current motor (BLDC), a planetary gearbox, and a brake mechanism are usually located inside the hub-motor, which can significantly simplify the design of the transmission, reduce the size and weight [1, 2].

The issues of diagnostics, development, and research of fault-tolerant control algorithms in case of a failure of the electrical part of the BLDC: inverter elements, position sensors, short circuits, winding bypass are discussed in detail in a large number of works, for example, [3–12].

On the other hand, during operation, due to wear or excessive loads, defects may occur in the mechanical components of the hub-motors (bearings, shafts, planetary gears) [13]. A number of studies [14-18] deal with the design and construction of models of hub-motors, describing the mechanical and electromagnetic phenomena. However, the influence of defects in the mechanical components of hub-motors on the overall dynamics of the BLDC and AGV control systems, in our opinion, is still not been studied enough. The occurrence of such malfunctions can cause a deterioration in the quality of control of the speed of rotation of the BLDC and failures of the onboard AGV systems.
In low-cost hub-motors, the risk of failure of mechanical components increases significantly due to savings on materials and simplification of manufacturing technology. For example, exceeding the nominal load of the hub-motor at the time of start-up can lead to damage to the teeth of the gears of the gearbox, which is especially important for planetary gears with plastic gears. These failures in the case of using a large number of mobile robots might cause congestion and deadlocks in the AGV system [19] and, as a result, lead to economic losses. Therefore, when developing an AGV based on low-cost hub-motors, it is important to investigate the effect of mechanical component failures on the overall dynamics of movement, as well as to investigate the possibility of restoring performance through the use of fault-tolerant control algorithms.

The study of the influence of defects in the mechanical components of hub-motors on the dynamics of control systems on physical AGV prototypes requires large material costs. Therefore it is advisable to use methods of mathematical and computer modelling. In this paper, using the technology of virtual prototyping, we study the effect of breaking the teeth of the sun gear of the planetary gear of the hub-motor on the general dynamics of the AGV with a differential drive. The chassis of such an AGV is most often diamond-shaped and is built based on two steered hub-motors and two caster wheels. At the same time, BLDC rotation speed control systems in the composition of hub-motors determine the dynamic properties of the entire AGV. In [20], the virtual prototype of the Green E-motion hub-motor, implemented in the MSC Adams environment with a BLDC rotation speed control system built-in Matlab Simulink is described. The resulting virtual prototype of the mechanical part of the control plant was integrated into the model of the control system for the dynamics co-simulation. However, the parameters of the model of the hub-motor and BLDC were not experimentally clarified. Also, there was used a simplified model of the planetary gearbox, which is not possible to simulate play and breakage of teeth. Therefore, an accurate and validated hub-motor with the BLDC control system model is required to study AGV performance under mechanical elements faults.

2. Materials and methods
The model of the Green E-Motion hub-motor speed control system as part of a differential drive AGV, implemented in Matlab Simulink, is shown in Figure 1. A virtual prototype of AGV with hub-motors, implemented in the MSC Adams software, is integrated to the BLDC subroutine (Figure 2), by which the dynamics of the mechanical part of the system is calculated in co-simulation mode. Also in this block, trapezoidal inverse EMFs, rotor angular positions in accordance with signals from Hall sensors, and electric torques arriving at the mechanical BLDC models are calculated. The model of the control system for the rotation speed of each BLDC (Figure 3) includes PI current and speed controllers, a PWM subroutine, an “SW Control” subroutine for IGBT switching using the “Softchop” method, and a block that implements a 3-phase inverter.

Every hub-motor model contains ABS plastic planetary gear with gear ratio 4.57:1, the motor with rotor and stator, and tire. The driving torque of the BLDC rotates the sun gear of the planetary gearbox, to the satellites of which a carrier is attached. The carrier rigidly fixed with the axle of the hub-motor. Caster wheels and hub-motors are mounted on the casing of the mobile robot and connected to the floor by contact forces, which also define static and dynamic friction. In the 3D model of the planetary gearbox of the right hub-motor, there are no three teeth of the ring gear. In order to provide the possibility of a detailed simulation of nonlinear phenomena in a planetary gearbox, including in case of tooth breakage, 3D-contact forces (Solid-to-Solid) with the presence of friction in the model are used to connect the gears.

In order to perform validation of the hub-motor virtual prototype, a laboratory setup was developed, the structure and appearance of which are shown in Figure 5, a and b, respectively. For identifying the BLDC parameters, the methods described in [21, 22] were used, taking into account that the motor is connected to a planetary gearbox, the ring gear of which is connected to the rim of the hub-motor. Incremental encoders based on Hall sensors, which, due to the decoding M-method [23], are used for obtaining information about the speed of rotation, are used to obtain information about the speed of rotation, to eliminate the influence of this phenomenon on the results, the gear is
connected to the motor wheel analogue tachogenerator based on the Maxon RE25 electric motor. The control unit includes a speed controller with PWM, a 3-phase inverter, a decoder of signals from Hall sensors. The current was measured using the current sensor ACS712ELCTR-20A-T. Linear voltages, signals from Hall sensors, tachogenerator, and a current sensor were recorded by a GW Instek GDS-72204 electronic oscilloscope. The identification of contact force parameters was carried out by iterative methods by comparison with the virtual prototype of the left wheel when the contact of the hub-motors with the floor was off, and the position of the AGV was fixed.

**Figure 1.** Co-simulation model of the AGV control system.

**Figure 2.** BLDC subsystem with Adams control plant.

**Figure 3.** BLDC control subsystem.

**Figure 4.** Virtual prototype of a mobile robot with hub-motors.
3. Results and Discussion

During the identification process, the BLDC parameters used in the Green E-Motion hub-motor, which are presented in Table 1, were determined.

| Parameter                  | Unit       | Value     | Parameter                  | Unit       | Value |
|----------------------------|------------|-----------|----------------------------|------------|-------|
| Hub-motor inertia, $J$     | kg·m$^2$   | 8.76E-4   | Number of pole pairs, $p$  | –          | 10    |
| Speed constant, $k_e$      | V·s / rad | 8.1E-2    | Hub-motor Mechanical time constant, $T_m$ | ms         | 35    |
| Torque constant, $k_t$     | N·m / A   | 8.1E-2    | Modulation Frequency, $f$  | kHz        | 16    |
| Terminal resistance, $R_a$ | Ω          | 0.155     | Terminal inductance $L_a$  | H          | 1.45E-4 |

Experimental Hub-motor and its virtual prototype are tested in steady state mode at 85 rad/s reference speed for the BLDC control system. The line voltage in phase A, corresponding Hall Effect Sensor signal $H_a$, and Phase Current $I_a$ of experimental BLDC motor drive and its co-simulation model in steady-state mode for hub-motor are shown in Figure 6. Good agreement between simulation and experiment results in steady-state and step response modes validates the Hub-motor virtual prototype.

![Diagram of experimental test setup](image-url)

**Figure 5.** Experimental test setup of Hub-motor with BLDC.

![Diagram of results](image-url)

**Figure 6.** Computer simulation and laboratory test setup results for steady-state mode.

During studying the influence of the sun gear defect, the acceleration and rectilinear motion at the
maximum speed of the AGV was simulated. The mass of AGV without motor wheels is 65 kg; the mass of each Hub-motors is 3.8 kg. The results of the hub-motors dynamics co-simulation mounted in the AGV are presented in Figure 7. As you can be seen, in the “defective” hub-motor there are slight fluctuations in the speed and torque of the BLDC with the frequency of the fundamental harmonic corresponding with the speed of the hub-motor. The most noticeable fluctuations are at the time of starting of the hub-motor when it develops more torque.

In the hub-motor itself, fluctuations in rotational speed are absent due to the influence of backlash and damping. Thus, this defect does not affect the dynamics of the AGV motion itself. However, this increases the load on the corresponding unbroken teeth of the planets and ring, which can subsequently lead to their breakage. For diagnosing the presence of a defect in three teeth of the ring gear, it is not possible to use information about the rotational speed in the case of using Hall sensors due to discretization. Therefore, fluctuations in the torque should be analyzed according to the readings of the current sensor. At the same time, using the developed virtual prototype, it is possible to form an appropriate data set for the training of neural network tools of systems that can be used for automatic diagnosis of hub-motor failures.

Figure 7. Results of the AGV Hub-motor dynamics of computer simulation.

4. Conclusion
In this work, we studied the dynamics of hub-motors mounted in the AGV in the presence of broken teeth of the ring gear of the planetary gearbox of the them. It was established that such a breakdown is not critical for the functioning of the AGV but at the same time the load on the other teeth of the planetary mechanism participating in the movement at the moment of passage of the defective place increases. The source of information for diagnosing the considered malfunction can be signals from the BLDC current sensors.
The use of 3D contacts in the planetary gearbox of the hub-motors makes it possible to study in more detail the influence of nonlinear phenomena on the dynamics of the BLDC control systems. After a small modernization of the presented virtual prototype, other defects in the mechanical system of the hub-motors can be investigated: breakdowns of other gear teeth, misalignment, the presence of extraneous elements. A more detailed study of AGV positioning systems also becomes possible.

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