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SIMULATION AND REAL-TIME APPLICATION OF THE LOAD CELL-BASED SEGWAY

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Abstract

In this study, real-time application and simulation of the load cell-based Segway was carried out by using an STM32F103 microcontroller. The Brushless Direct Current Motor (BLDC) current and speed information was recorded on the SD card simultaneously during the real-time application of the vehicle. The BLDC parameters required for the simulation of the Segway were entered into the block diagram created in Matlab/Simulink interface. Then the load cell-based Segway was simulated. As a result of the simulation, the determined phase currents were compared with the real-time application results. In addition, the repetition test of the load cells was performed, and 99.9% correlation coefficients were obtained from the measurement of each load cell. As a result of this process, the measurement error rate of the load cells was determined as 0.01%. Finally, the currents of the BLDC motors were compared with the simulation study and the real-time application. The similarity of the currents with each other was obtained with an error rate of approximately 1.5–2%.

Key words: Segway, load cell, BLDC, microcontroller, simulation, real-time application

1. Introduction. There are many alternative vehicle types for transportation. However, especially in recent years, scientists have focused their studies on electric vehicles due to air pollution and economic reasons. The power of electric

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motors and the range of the vehicle are considered effective parameters in electric vehicle design. One of the critical problems in electric vehicles is that the battery charging times are pretty long. Fuel filling times in internal combustion vehicles are relatively short compared to the charging time of batteries. For this reason, various methods are tried in some studies to shorten the charging process. One of these methods is to design more ergonomic vehicles by reducing the dimensions. For this purpose, the small and compact electric vehicle named Segway entered the literature in 2001 [1]. Segway is a mobile robot that can balance itself on two wheels. It is preferred in many applications due to its simplicity, small dimensions, and high manoeuvrability in narrow places. Segways are used as a transportation vehicle in many areas such as airports, golf courses, security companies, hospitals, and large factories. Additionally, it is requested to perform various tasks in applications where Segway is used as a mobile robot. Examples of Segway-based applications are autonomous moving robots that map their surroundings with the camera module, robots that can perform tasks by remote control, and mobile robots designed to transport various loads.

It is seen that various sensors and algorithms are used to control Segway when the studies in the literature are examined. The control of the Segway system is usually carried out using gyroscopes and accelerometer sensors [2–4]. There are also studies with different control methods. These methods are Linear Quadratic Regulator (LQR), Proportional, Integral and Derivative (PID), Fuzzy Logic, and Artificial Neural Network-based control methods [2–14].

Simulation [4,5] and real-time [2,3,6–9] based studies related to Segway are conducted in the literature. It is one of the essential issues to read the signals received from the electronic and control system without error to work stably. For this reason, studies are carried out to filter the noise of the read signals from the sensors. Although many different methods are used in filtering the signals, it is observed that the Kalman filter is mainly used [7,10]. Studies have been carried out to reduce the time of receiving, sending, and filtering data from sensors in robots [7]. In addition, robots increase their mobility by detecting obstacles with the use of laser sensors [8]. The subjects of remote control are also emphasized in some robot-based studies [2,11].

One of the essential parts of robots is battery packs used as an energy source. It is one of the critical sections in two-wheel robot systems since battery systems provide the energy required by the systems. The working times of the robots vary in direct proportion to the energy stored in the batteries. For this reason, optimization-based studies are carried out to increase the range of the robot's motion [15,16]. Genetic Algorithm optimization and Bacteria herd optimization were used to work more stable at LQR controlled two-wheeled balance robot. According to a study, it is shown that bacteria flock optimization-based control works better in a simulation environment [12]. A more stable and safer driving is achieved using a robust-based high-degree moving sliding-mode control algorithm

in the two-wheeled electric vehicle [17]. Also, there are studies on the types of tires used for the stable operation of Segway [18].

In this study, load cells were used to control the Segway system. Thus, the Segway was controlled based on load cells for the first time. The centre of gravity tilt information of the person was obtained using load cells. The Segway's motor speed was controlled using a PID controller. The system's rising time, settling time, and overrun values were obtained as 82 ms, 182 ms, and 6 rpm, respectively. The dynamic behaviour (speed and current values) of the Segway motors reached the desired value quickly without overrun too much, as can be seen from the obtained values. In this study, Segway's simulation was successfully modelled in a simulation environment, and its real-time application was also carried out. The movement of the Segway system was successfully implemented in the simulation and real-time application environment. The obtained data in the simulation environment were compared with the real-time application, and consistent results were obtained.

2. Materials and methods. ***Mathematical modelling of the Segway's dynamic behaviour.*** Brushless Direct Current Motor (BLDC) is widely used in industry because it provides high torque, silent operation, and robust construction. It is primarily used in aviation, medicine, computer technologies, industrial automation, military applications, environments with the risk of glare and burning, and robotics. The mathematical equations required for the control of BLDC are mentioned in [19].

The torque force generated by BLDC should be more than the resistance forces required for the movement of the Segway. Therefore, the forces affecting BLDC must be determined. The forces of resistance that affect the movement of a vehicle are grade, rolling, acceleration, and aerodynamic resistance. The aerodynamic and acceleration resistances are ignored during the calculations since these values are limited on the Segway.

The steering angle of the Segway is determined according to the differences of the load cells on the right and left sides. The maximum steering angle (5°) is determined with the designed algorithm to prevent accidents when the difference between right and left load cells is too high. The user tends to lean forward or backward at a certain angle while controlling the Segway. Pitching angle (ψ) is the angle between the user and the ground. Dynamic change of pitching angle according to the user is carried out by the load cells.

Accidents that may occur can be prevented by limiting the user's exceeding the maximum pitching angle by the software. The maximum pitching angle ($\mathbf{\Psi}_{\max}$) is given in Equation 1. It depends on the Segway's mass (M), user's mass (m), acceleration (a), and gravitational acceleration (g). $\mathbf{\Psi}$ of the Segway is calculated after $\mathbf{\Psi}_{\max}$ is determined. This angle is given in Equation 2 depending on the relative percentage of the mass difference in the front (LC_F) and the rear load cells (LC_R).

$$\Psi_{\max} = \arctan\left(\frac{(M+m).a}{M.g}\right) \tag{1}$$

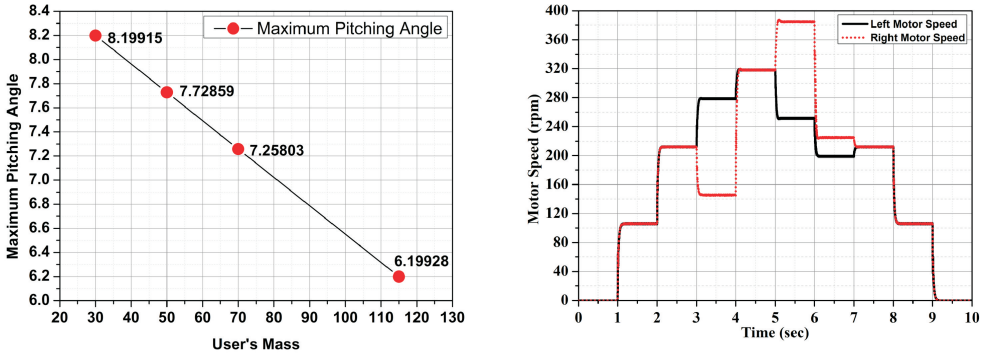
$$\Psi = \Psi_{\max} * \frac{LC_F - LC_R}{LC_F + LC_R}. \tag{2}$$

The maximum speed is 20 km/h. The speed of the motors is changed according to the difference of the values obtained from the front and rear load cells in the created control system. Differences between the values read from the front, and the rear load cells are taken. Then, the relative percentage is obtained using these values. When the Segway's steering angle value is zero degrees, the reference speed is distributed equally to the right (W_{right}) and left (W_{left}) wheels. However, when the steering angle is different from zero, W_{right} and W_{left} change according to the steering angle.

The real-time design of the load cell-based Segway system. The user must press on four load cells; otherwise the motor driver prevents triggering the motor with the designed algorithm. It is aimed to prevent the users from falling while getting on the Segway with this precaution. The motors are controlled according to the load cells after the motors are activated. The currents drawn by the motors are measured with the help of the ACS712 and written to the SD card. The battery control unit checks the battery of the system and decides whether the system can continue to operate. The data about motor phase positions and which phase would be triggered are learned from the Hall Effect sensor. Phases are triggered in the correct order with this data. In the real-time application, two motor drivers that are Wiwi K–D1.5 card number are used. It has 1200 W power, 40 A current capacity, and a voltage range of 48–84 V. The Segway's battery pack technical specifications are 54.8 V, 4300 mAh, and 236 Wh.

3. Experimental results and discussion. ***The simulation of the load cell-based Segway system and results.*** Four load cells are used in the system. The Segway moves forward when the sum of front-load cells force is greater than the sum of the rear-load cells force. In the opposite case, it will move backward. Likewise, the Segway turns to the right when the sum of the load cells on the right side is more than the load cells on the left side. It will turn to the left in the opposite case. The distribution of the user's mass on the simulation is carried out with a slider in Matlab/Simulink environment. Firstly, the user's mass has to be selected. It is designed to be 30 to 115 kg. After that, the total mass is distributed to four load cells. After the front and rear values were determined, left and right values were calculated. The motor speeds are also calculated in the same way.

The $\Psi_{\max}$ according to user's mass is given in Fig. 1 (a). $\Psi_{\max}$ is decreased when the user's mass increases. It means these parameters have inverse pro-



(a) (b)

Fig. 1. (a) The $\mathbf{\Psi}_{\max}$ according to user's mass; (b) The motor speeds of Segway

portions to each other. The motor speed values are calculated on the Segway simulation interface. The graph of the speeds is given in Fig. 1 (b).

The real-time application of the load cell-based Segway. In this study, the algorithm of the Segway was designed by using an STM32F103C8T6 model microcontroller with the ARM architecture. The Segway firstly balances itself to be in an upright position by receiving data over the multi-sensor card. PID control method is used during this balancing process. The output graph of the system was examined by trial and error in determining the PID parameters. The most successful parameters were selected as PID parameters. The HX711 module with a 24-bit ADC resolution is used since the usage precision of the Segway is of vital importance. Thus, the system was controlled more precisely. The view of the load cell-based Segway is given in Fig. 2.

The desired information data is written on the LCD screen of the control card. Likewise, after using the Segway, the data is saved to SD card to make

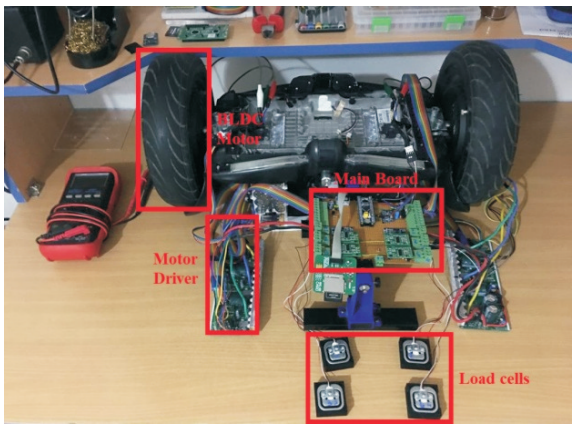


Fig. 2. The real-time implementation of the Segway

an analysis on these data. Whether they accurately measure the weight applied on the load cells was tested with Shimpo FGJN–50 force gauge device. Each load cell is loaded in 5 kg increments from 5 kg to 40 kg at 10 seconds intervals, respectively. The measurement results are given in Table 1. The deviations were extracted ±430, ±330, ±150, ±300, respectively. Then, correlation values were calculated as 0.99 for each.

T a b l e 1

Measured load cell values with the different reference values

Reference Kg	Load Cell 1	Load Cell 2	Load Cell 3	Load Cell 4
5.00	5.10	4.90	4.90	5.00
10.00	10.11	10.18	10.15	10.03
15.00	15.29	15.33	14.98	15.30
20.00	20.40	20.12	20.05	19.96
25.00	25.43	25.26	25.02	25.07
30.00	29.96	29.98	30.30	30.16
35.00	35.42	35.19	34.8	35.22
40.00	40.31	39.71	40.65	40.41

The system is operated under empty load, taking into account the security measures. To compare the simulation with the real-time system, a force to compensate for the loss forces is created in the simulation. The current graphs drawn by the left BLDC in the simulation and implementation are given in Fig. 3.

The speeds of the right and left motors are measured and according to the pressure applied to the load cells on the right and left sides by a user who gives

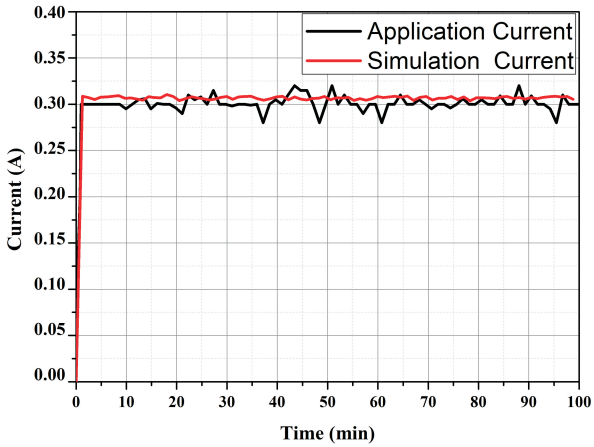


Fig. 3. The currents from simulation and real-time application

60% of the user's mass forward. For each 1% load difference, it corresponds to an average of 7.5 rpm in motors.

It is seen that scientists generally focus on the simulation of two-wheeled robot systems when the literature studies are examined. Gyroscope and accelerometer sensors were usually used in the two-wheeled control of the system [17,18,20]. In this study, the load cell sensor was used. The system was controlled with the pitching angle specific to the user using the user's mass information. Thus, the user was prevented from exceeding the maximum pitch attitude.

This system has the following advantages compared to literature. Thanks to the load cell, the output of the dynamic model can be updated instantly according to the user. The steering angle is derived by comparing the ratio of right-left side load cells. Thus, there is no need for any equipment for the steering angle. Motors are not triggered unless each load cell is pressurized. It is carried out to prevent accidents that may occur while the user is riding the Segway. The sensitivity of the system was increased by using 24-bit ADC. Twelve different data were saved on the memory card for using the examinations and behaviour analysis of the system.

4. Conclusion. In this study, the load cell-based Segway control system was designed and implemented. The use of load cells is one of the most important aspects that distinguish this study from other studies in the literature. Mathematical modelling, simulation, and real-time application of the load cell-based Segway were performed within the scope of the study. Thanks to the load cells, the output of the dynamic model of the system could be updated instantly. It also plays an essential role in determining the maximum pitching angle according to the user. The maximum pitching angle can be determined with the mass information of the user. This ensures that the user can drive the motors without exceeding the maximum pitching angle, reducing the danger of the user falling from the vehicle. The initial operation of the motors is dependent on the condition that there is a load on four load cells. Thus, the risk of the driver falling off the Segway is minimized. In future studies, various improvements can be performed to make the system work better. The noise from the equipment can be suppressed using various filters. Thus, the system will be more stable. Using adaptive control algorithm as the control algorithm could make the system more efficient.

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