Modeling, simulation and hardware implementation of a self-balancing robot

The aim of this paper is modeling, simulation and implementation of a self-balancing robot. The problem of a self-balancing robot is considered as a problem of inverted pendulum stabilisation, while a DC motor is used as the drive motor.

Deflection angle indicates the angle by which is the robot inclined to a side, in other words, by how many degrees is the y-axis of the robot rotated from the absolute y-axis, so that the center of wheels is exactly at the section of these axises.

In simulation, the deflection angle is measured in four ways: using a gyroscope, an accelerometer, both gyroscope and accelerometer in combination using a complementary filter and both gyroscope and accelerometer in combination using Kalman filter. These sensors are placed on the apex of the robot in order to maximise the amplitude of measured values. Two types of stabilisation controllers are used: PID and LQR. Respective performance of these regulators are compared relative to the way that the angle is obtained.

Results of the simulation in which only a gyroscope is used indicate that this sensor accumulates measuring error exceptionally fast, which results in a value over π after just one second. Because of this, stabilisation is not possible regardless of the regulator.

In the case of measuring using an accelerometer, a constant measuring error is observed and that the presence of noise is more apparent than when a filter is used. Furthermore, noise’s amplitude is greater with LQR regulator as a consequence of flickering noise, which is expected because the current deflection angle changes at a quicker rate using PID. Contrary to LQR, stabilisation using PID regulator has overshoot.

When a complementary filter is used, the gyroscope error accumulation is not observed and both constant error and noise of an accelerometer are less pronounced. Similarly to previous case, noise is more apparent with LQR, but overall noise is lower.

When Kalman filter is used, properties of the error and noise are similar to those from complementary filter, except that the noise is of less amplitude. Regardless of the regulator type, stabilisation is achieved with the lowest noise of all four cases. Noise is again lower when LQR regulator is used due to the flickering noise.

All simulation hypotheses set during the initial problem analysis and modeling are confirmed: robot can successfully stabilise regardless of regulator type, except when measurements are only acquired from a gyroscope.

Unlike in simulation, PID regulator is only implemented in hardware where the measurements represent output of a complementary filter of both gyroscope and accelerometer. Major setback in hardware system emerged as a significant free movement in transfer of the motor torque to the wheel axle; as a consequence, the robot can be displaced from balance and disable any further stabilisation. The system is successfully put into stable oscillatory movement, but the stabilisation is not possible and the hypothesis is not confirmed.

To review the plausibility of this hypothesis, further work should focus on removing the free movement in mechanical transfer. Also, stabilisator performance should be observed when the center of robot’s mass is shifted downwards, in other words, when additional weight is added to its base.

Modeliranje, simulacija i implementacija samobalansirajućeg robota

Cilj ovog rada je modeliranje, simulacija i izrada samobalansirajućeg robota. Samobalansirajući robot je mehanički sistem za kretanje po ravnim površinama sa kojima je u kontaktu preko para točkova na jednoj osovini. Osnovna funkcionalnost ovakvog robota je samostalno održavanje centra mase iznad ose rotacije.

Problem stabilizacije posmatran je kao problem stabilizacije inverznog fizičkog klatna, dok je kao pogonski motor korišćen DC motor. U simulaciji, ugao otklona robota od pravca gravitacije, meren je na četiri različita načina: pomoću žiroskopa, pomoću akcelerometra, pomoću žiroskopa i akcelerometra zajedno u kombinaciji sa komplementarnim filterom i pomoću žiroskopa i akcelerometra zajedno u kombinaciji sa Kalmanovim filterom.

U hardverskoj implementaciji korišćeni su žiroskop i akcelerometar u kombinaciji sa komplemetarnim filterom. U simulaciji su korišćene dve vrste stabilizatora: PID i LQR, dok je u hardveru implementiran samo PID regulator. Poređene su performanse stabilizacije sa ovim stabilizatorima u odnosu na način estimacije ugla.

U simulaciji dobijeno je da je stabilizacija nemoguća ukoliko se koristi samo žiroskop, dok je stabilizacija u ostalim slučajevima moguća. Najbolje performanse su dobijene ako se ugao otklona meri pomoću žiroskopa i akcelerometra zajedno u kombinaciji sa Kalmanovim filterom. U hardveru nije bilo moguće izvršiti potpunu stabilizaciju sistema zbog velikog slobodnog hoda motora jer bi se robot stalno izvodio iz ravnotežnog položaja.