Abstract: This paper deals with the design of a device for measuring the steering wheel angle. The main goal was to design a basic concept of the device which is using data gathered from three accelerometers in the reconstruction algorithm to get the steering wheel angle. Furthermore, the paper deals with problems related to reconstruction algorithm errors and design improvements.

Keywords: Sensors, MEMS technology, Accelerometer, Gyroscope, Arduino, I2C, SPI, MATLAB, Simulink, Mathematical model, Measurement, Rotation angle, Microcontroller

1 INTRODUCTION

Observation of driver behavior is essential for the design of safety measures on roads, in cars, but also other areas of motoring research. Among the most important data for observing driver’s behavior are the data of steering wheel angle.

The sensor of steering wheel angle is part of the project, that tries to monitor driver behavior a highway drive. To sense rotation angle we have chosen a slightly unconventional method based on three accelerometers, which sense the inclination to gravitation acceleration. A big advantage of this method is the portability and independence of the car model. Thanks to this method, we do not have to deal with communication with control units of different car models to obtain data of steering wheel angle. Data from the sensor of steering wheel angle will be sent to a computer, where they will be gathered and analyzed with other data from other sensors.

2 HARDWARE

The whole device consists of a microcontroller Arduino UNO and three inertial sensors GY-91 with a 3-axis accelerometer and 3-axis gyroscope. GY-91 allows communicating with a microcontroller using SPI or IIC bus. For communication between Arduino and inertial sensor, we’ve chosen SPI bus because SPI bus has a higher transfer speed than IIC. Also, IIC has a problem with 3 and more same devices on a single bus, because GY-91 has just two optional IIC addresses, so there would be a collision on the bus.

3 RECONSTRUCTION ALGORITHM

As I mentioned before, the whole device consists of three inertial sensors. Two of them are situated directly on the steering wheel and the third sensor is used as a reference. Outline of sensor placement is illustrated by Figure 1. For the start, we will consider a steering wheel perpendicular to the ground. The principle of measuring steering wheel angle is based on measuring the inclination of the gravitational acceleration vector relative to the coordinate system of each accelerometer on the steering wheel. Unfortunately, both accelerometers are not affected only by gravitational force, but also by
centrifugal and inertial force while turning the steering wheel. If we take a closer look at the Figure 1, we can realize, that centrifugal and inertial force, which affect both sensors on the steering wheel has the same magnitude. The effect of gravitational force differs. To get rid of the effect caused by centrifugal and inertial force, we subtract corresponding force components from each sensor. After this, we get Equations (1) and (2)

\[
\vec{a}_1^g = (-g \sin(\theta - \phi), -g \cos(\theta - \phi))
\]

(1)

\[
\vec{a}_2^g = (-g \cos(\theta - \phi), g \sin(\theta - \phi))
\]

(2)

where \( g \) is the magnitude of acceleration caused by the outer world, \( \phi \) is the angle of its rotation (see Figure 1) and \( \theta \) is steering wheel angle. If \( \theta \) is positive, the steering wheel is turned in the positive sense of rotation. To ensure that components of centrifugal and inertial force cancel out, we have to synchronize the sampling of both accelerometers. To ensure that the data from both accelerometers are synchronized, we used FIFOs of the sensors. We also have to fasten inertial sensors on the steering wheel as precisely as possible. During a car drive, we have to consider disturbances. For example car shocks, or forces affecting the car during turning, etc. These effects can be compensated using a third accelerometer, which detects the resultant of all forces affecting the car instead of just the gravitational force mentioned earlier. By adjusting the equations (1) and (2) we can get (3), by means of which we can determine the angle of the steering wheel.

\[
\theta = \arcsin\left(\frac{a_{1x} - a_{2x} + a_{1y} - a_{2y}}{-2\sqrt{a_{1x}^2 + a_{1y}^2}}\right) + \arctan\frac{g_y}{g_x}
\]

(3)

Using rotation matrix, we can generalise this equation to an arbitrarily inclined steering wheel. We arrive at two equivalents of Equation (3), which use either arccos or arcsin. In the final algorithm we dynamically combine these two functions in order to minimize effect of noise and maximize accuracy. For that reason we divide measured interval \((-\pi, \pi)\) to five smaller intervals.

4 MOUNTING OF SENSORS ON THE STEERING WHEEL

Inertial sensors attached to the steering wheel have to meet some requirements. They have to be fastened strongly enough, so they do not move during steering wheel rotation. Concurrently they have to be placed perpendicular to each other, at the same distance from the axis of rotation, for the algorithm to work properly. Furthermore, the sensor position cannot limit driver in-vehicle control or block certain safety or control features (e.g., airbag or horn).

Therefore we have created a system very similar to a wristwatch. It consists of a belt from raw material and a buckle from a 3D printer with an inertial sensor case attached to it. When we want to
place the sensor, we just turn around the steering wheel frame belt through the buckle and tighten it up. Sensors are placed on the steering wheel according to Figure 1, so they do not disturb the driver, because recommended position of the hand on the wheel is (if you imagine dial) on 2 and 10 hours.

5 IMPROVEMENTS OF THE RECONSTRUCTION ALGORITHM

In Section 3, a basic algorithm calculating steering wheel angle was described. In this algorithm, we neglected some facts like the tilt of the steering wheel or inaccuracy in inertial sensor position.

5.1 Compensation of sensor rotation around x axis

The way the sensors are attached ensures his stability on the y- and z-axis. Unfortunately, sensors can be rotated around the x-axis. To determine the sensor rotation angle, we devised a calibration procedure. During the procedure user oscillate with the steering wheel. Based on data from the gyroscope we can determine this angle. Then we compensate this deviation using a rotation matrix.

5.2 Determination of steering wheel tilt

In Section 3 we assumed, that the steering wheel is perpendicular to the ground. Normally the steering wheel tilt is adjustable. Therefore before every measurement, we have to determine the steering wheel tilt and then compensate it with a rotation matrix. Using accelerometers and the angle that their axes make with the gravitational acceleration vector, we determine the tilt angle of the steering wheel.

5.3 Determination of multiple rotations

As mentioned above, the interval $(-\pi, \pi)$ in which we are calculating rotation angle is divided into five smaller intervals. The program remembers the last interval the steering wheel was in. If there is a transition between the extreme intervals, we add or subtract one from the state variable $k$. The resulting rotation angle will be given by the sum of the rotation angle based on the equation 3 and the $k$-multiple of $2\pi$ rad.

5.4 Usage of complementary filter

For further enhancement of the basic algorithm, we combined the data from accelerometer system with the measurement using gyroscopes. To measure rotation using gyroscopes is very simple. If sensors are perfectly attached, then rotation angle corresponds to the integral of z-axis signal of both accelerometers on the steering wheel. Gyroscopes, unfortunately, measure signal with an offset, which is present even then if the gyroscope is not rotating. Therefore gyroscopes have problems with noise on low frequencies. On the other hand, accelerometers have problems with noise on high frequencies.

A complementary filter is designed in a frequency domain by taking the high-frequency part of the spectrum from the data we obtain from gyroscopes. We complement this data with the data obtained from accelerometers so that we again obtain the entire frequency spectrum. The complementary filter describes the Equation (4), where $\omega$ is an optional parameter chosen from the interval $(0, 1)$.

$$\theta = \omega \theta_{gyro} + (1 - \omega)\theta_{acc}$$

6 PRACTICAL IMPLEMENTATION OF DEVICE PROTOTYPE

For practical implementation of the device prototype and verification of its functionality, we originally intended to use a driving simulator in the laboratories of BUT FEEC. Due to the current situation,
we were forced to test this device prototype on a gaming steering wheel *Thrustmaster Ferrari Red Legend Edition*. This steering wheel has some limitations including limited rotation range, which was approximately $\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$. Therefore we could not test the system’s capability to detect multiple rotations.

Because this prototype was tested at home, we did not have to comply with some requirements for the device, which are necessary for its actual use. For example, we placed the control microcontroller in the center of the steering wheel, which must be free in the car due to the presence of an airbag. The microcontroller is connected to the sensors via a non-soldering field. The final version of the device prototype can be seen in the Figure 2.

![Figure 2: Final version of device prototype](image)

The final device should work so that each inertial sensor will have its own microcontroller (e.g., Arduino Nano), which will send wirelessly directly to the data gatherer. Wireless communication is not part of this paper.

7 CONCLUSION

The paper aimed to create a device for measuring the rotation of steering wheel angle. It was important for the device to be portable and independent of the type of vehicle. The steering wheel angle is obtained from the data of three inertial sensors. After building the basic algorithm, we extended it to detect and compensate for the rotation of the sensors and the steering wheel itself compared to the ideal position. Because the steering wheel in classic cars can make more turns on one side, we have extended the interval in which the device can measure. Finally, we used a complementary filter to improve the measurement results by combining data from accelerometers and gyroscopes. We first simulated the device in the MATLAB Simulink environment and then we assembled its prototype, attached it to the game steering wheel and tested it. The results of the sensor are very good and correspond to the actual angle of rotation.

REFERENCES

