Hand-Gesture-Controlled Obstacle Avoiding Robot with Haptic Feedback

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The objective of this project is to develop an "Obstacle Avoiding Robot (OAR)" that moves around a room and avoids obstacles when it encounters them. The moving in the environment will not be automated, but rather controlled by a "Smart Hand (SH)" that captures basic gestures of the human hand. The detection of the obstacle will be provided to the user as haptic vibrations with pulses indicating how near is the obstacle. This feedback allows the human to avoid this obstacle by changing the moving direction of the OAR. Since the sensors used for the measuring the angles of the gesture and the sensors used for measuring the distances are noisy, a filtering and a sensor fusion is performed. Experiments and results show that the Kalman Filter and the Complementary Filter provides better estimations depending on the sensor.

1 Introduction and Project Description

During the master degree program, we realized our HSA project to implement the different learned concepts received in the lecture. We have chosen to work on a system that uses a micro-controller unit (MCU), sensors and actuators.

Since robotics is a vast field that includes a large number of subjects such as that computer science, electronics, mechanics etc, we found interesting to create a more attractive tool that could be further improved and used in the industry. We have chosen to design an educational robot capable to implement these materials, easy to assemble and cheap. It will have to gather elements allowing to carry out experiments in order to show the scientific view of the implementation. We therefore want to design a robot capable of interacting with the environment by means of sensors. It will be ordered using C/C++ (IDE: AtmelStudio) which will have the following interest to highlight the objectives mentioned above. We can divide our work into four major phases.

First the design of a mechanical base for the driven four-wheel Obstacle Avoiding Robot (OAR) and the driving Smart Hand (SH) unit. Then the integration of the electronics of controls and micro-controllers. Afterwards, the programming of the single elements is done, whereby two perspectives are taken into consideration: the low-level including the generation of the control signals and the high-level including the signal-processing. Finally, the fusion of all elements is implemented to form the two subsystems: the OAR and the SH. Figure 1 shows the overall system.
In this report, we will try to detail the solutions chosen for this project. From this, we will explain the full development of our project during almost 6 weeks of work and we will show some experiments. For this purpose, the work is divided into three main parts: two parts will be dedicated to describe the OAR and the SH and one part will fuse both subsystems.

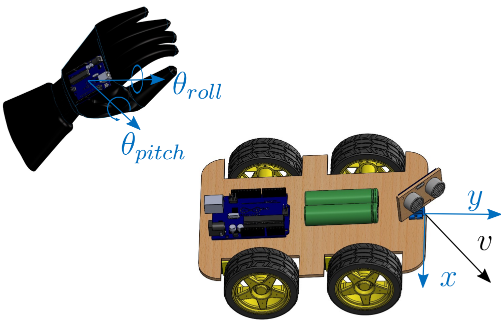

Figure 1: System Overview[1]

2 Obstacle Avoiding Robot

The first part of our work focused on the OAR. Starting by defining the micro-controller used, then by drawing the circuit schematic of the subsystem and then programming each part separately. The Table 1 describes all devices required for the assembly.

2.1 Micro-controller

The micro-controller represents therefore the brain of the subsystem. Because of the complexity of the project, we chose use the ATMega328p because of these properties. The MCU is an 8-bit micro-controller of the AVR family whose programming can be done in C/C++ language. It includes 3 GPIO ports (23 I/O pins in total), 2 8-bits timers and one 16 bit timer. Each timer could be used to generate 2 PWM signals by its different modes such as fast PWM mode, CTC

[1] Drawn using Solidworks 2018

Table 1: Hardware components used to build the Obstacle Avoiding Robot.

Device	**Function in the system**
MCU (Atmega328P) [2]	Includes the logical behavior of the subsystem, generators the control signal for the actuators and process the sensors data.
Radio TX/RX module (NRF24L01 2.4GHz) [3]	Transmits and receives signals.
Ultrasonic sensor (HC-SR04) [4]	Measures the distance to an object using sound-wave reflection.
Infrared sensors (SN-IRS-01) (3x)	Measures the distance to an object using light-wave reflection.
Servo (SG90)	Rotates the head of the robot that includes the ultrasonic sensor.
Gear Motors (4x)	Moves the robot.
H-Bridge (L298N) [5]	Provides the ability to fully control of the wheels and allows the robot to move forward, backward, to the right and to the left.

mode, etc. Moreover, an ADC is available with 10 bits resolution and could be shared by 6 inputs by using a multiplexer. An I2C-Bus (Inter Integrated Circuit) and a Serial Peripheral Interface (SPI) are also available. Various Interrupt Service Routines (ISRs) could be called by interrupt triggers. [2] All the necessary low-level functions are implemented within the scope of this project the Arduino Library was not used. Only the AVR library that includes the definitions of the registers, addresses, etc were included. Note that the system frequency is set to 16MHz.

2.2 Radio TX/RX module

The radio module nRF24L01 is a fully integrated radio module from Nordic Semiconductor. It is a radio module integrating everything necessary to transmit and receive data over the 2.4GHz frequency range using the Nordic's proprietary communication protocol called ”ShockBurst”. [3] The transmitting protocol layers (known as the OSI layers) are implemented in the hardware. Since the communication aspect is not the focus of this project, the slightly modified library

R24[2] were used, allowing a duplex transmission and reception of data.

2.3 Ultrasonic sensor

An ultrasonic distance sensor uses the principle of a laser sensor, but using sound waves (inaudible) instead of a light waves. They are much cheaper than a laser sensor, but also much less accurate. However, unlike infrared sensors, the ambient light and opacity of the surface in front of the sensor do not affect the measurement. This allows us to choose this sensor to estimate the distance of an obstacle in front of the OAR. The used sensor HC−SR04 operates with a supply voltage of 5 volts, has a measuring angle of about 15° and allows distance measurements between 2 cm and 4 m to be made with an accuracy of 3mm $\sim$ 1cm.
The operation concept of the sensor is entirely based on the speed of sound. This is how a measurement is taken:

- A $10\mu s$ HIGH pulse is sent to the TRIGGER pin of the sensor.
- The sensor then sends a series of 8 ultrasonic pulses at 40KHz.
- Ultrasound travels through the air until it hits an obstacle and returns in the opposite direction to the sensor.
- The sensor detects the echo and closes the measurement.

The signal on the ECHO pin of the sensor remains at HIGH during the reception of the reflected sound-wave, which allows the duration of the ultrasound round trip to be measured and therefore the distance to be determined as follows:

$$d = \frac{t \cdot v_{sound}}{2}, \tag{1}$$

where $v_{sound} = 340 m/s$ denotes the speed of sound and t is the duration of the pulse generated by the ECHO signal. Diving the whole by 2 is required, since the round trip time is considered.

The triggering, the pulse generation and the echo phase (reception) are shown in Figure 2. To improve the accuracy of the measurements, a Kalman filter was used. This filter can be applied to any type of system that can be described by a linear equation with a Gaussian noise, which is the case here. Such a system could be described as follows:

$$s[n] = as[n-1] + u[n] \tag{2}$$

[2]https://github.com/nRF24/RF24

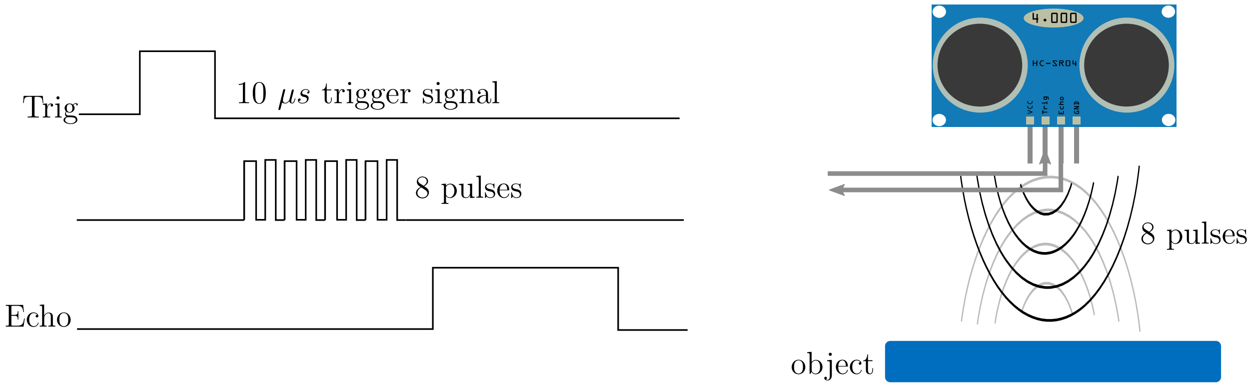

Figure 2: Transmission and reception of sound-wave using SR04 ultrasonic ranging module.[1]

$$x[n] = s[n] + w[n], \tag{3}$$

where u and w are zero mean gaussian noise with variances σ_u and σ_w respectively, x is a measurement, s is the real value to be estimated and a is a scalar coefficient. The idea of this filter is to provide an estimation of the current value based on a physical/mathematical model in case where the measured value is very uncertain (high variance). If the sensor provides a good measurement and the variance is therefore low, the kalman filter attenuates the prediction based on the mathematical model and puts more weights for the measurement. The gain of how much should the measured data be taken into consideration is called the kalman gain. Concretely, the Kalman filter performs two steps; the prediction and the update step. The prediction phase computes the prediction based on the mathematical model, as follows: [6]

$$\hat{s}[n|n-1] = a\hat{s}[n-1|n-1] \tag{4}$$

The kalman gain is computed as follows:

$$k[n] = \frac{M[n|n-1]}{\sigma^2 + M[n|n-1]}, \tag{5}$$

where $M[n|n-1] = a^2 M[n-1|n-1] + \sigma_u^2$ is the minimum square error estimation (MSE). The second phase is the correction step, where the measurement is taken into account and results in the following overall estimation of the real value:

$$\hat{s}[n|n] = \hat{s}[n|n-1] + k[n](x[n] - \hat{s}[n|n-1]) \tag{6}$$

Finally, a new MSE estimation is computed assuming the estimated value $\hat{s}[n|n]$ as the real value at step n.

$$M[n|n] = (1 - k[n])M[n|n-1] \tag{7}$$

Applying this filter to the measured distances, as shown in Figure 3, improves the accuracy of the estimation. In fact, suddenly appearing high peaks which does not fit the linear model and has high variance will be filtered out. Experiments showed that using this filter decreases the number of False Postives.

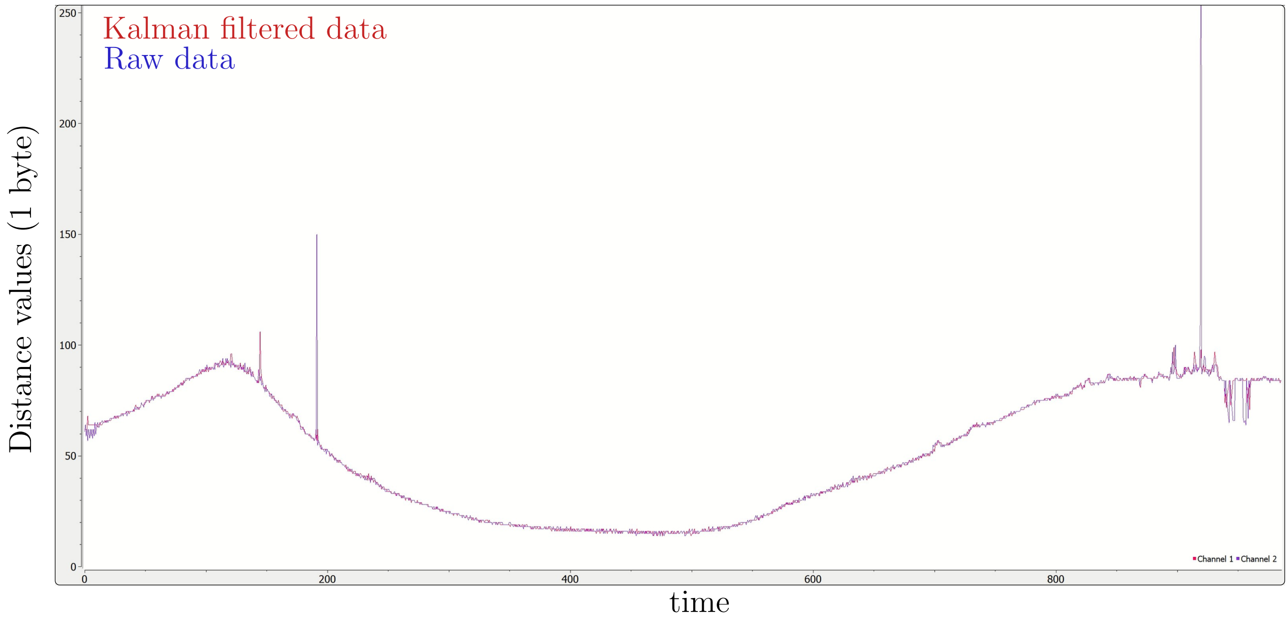

Figure 3: Filtered distances using Kalman vs. raw distances.

2.4 Infrared sensors

In order avoid additional collisions when driving the OAR backwards, to the right or to the left, 3 infrared sensors are added. We opted for infrared sensors since they are small and cheap. A ADC was implemented in order to read the analog distance signal.

2.5 Servo

We program a standard servo configuration with an update period of 50 Hz using PWM signal, which is generated using the 16-bit timer 1 in Clear Time on Compare Match mode (CTC-mode). The output signal is initially zero and starts counting. The compare match register triggers the internal ISR, which resets the output signal to zero. The servo moves its cursor position when the duty-cycle varies from 0.2 to 1.2 ms. By computing a the corresponding values for the 16-bit register OCR1A register and by trying different values within the range of that value, we end up with the interval [600, 2400], which corresponds to the angular range

[2]We are dealing with the binary classification, whether an obstacle is present or not.

[0°, 180°] (some degrees are discarded for safety).

$$OCR1A = \frac{t}{\frac{1}{f_{CPU}} \cdot prescaler} \tag{8}$$

Figure 4 shows two position examples of the servo and the control PWM signal used to set those positions. For the observation task of the OAR, we set a constant rotating rate to $1°/10ms$

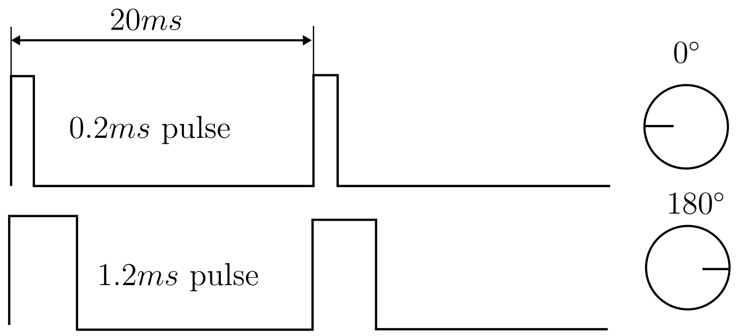

Figure 4: PWM signal controlling the Servo Motor.

covering 90° centered to 0.

2.6 Gear Motors and H-Bridge

First of all, a PWM signal in fast-PWM mode is used to control the rotation speed of the motor. As already mentioned, the PWM turns on and off the signal allowing a variation of the average voltage and therefore the electromagnetic force induced in the motor will vary. So, the speed is proportional to the duty-cycle of the PWM signal. In the fast-PWM non-inverting mode the signal will be set to low if it reaches the OCR value. It is set to high when the counter restarts the counting from 0.

In order to switch the rotation orientation of the motors, it is indispensable to reverse the direction of the current flow. For this purpose, an H-Bridge circuit is used, which fulfills this task by switching transistors or MOSFETs. Since the L298N bridge is able to only control two motors, the right side motors are connected in parallel and uses the first control port, and the left side motors are also connected in parallel and uses the second control port.

3 Smart Hand

The second part of our work is dedicated for the Smart Hand (SH). In particular the IMU unit will be the focus of this subsystem. The Table 2 describes all devices used to build the SH. The same micro-controller described in 2.1 and the same Radio TX/RX module described in

Table 2: Hardware components used to build the Smart Hand.

Device	**Function in the system**
MCU (Atmega328P)	Includes the logical behavior of the subsystem, generators the control signal for the actuators and process the sensors data.
Radio TX/RX module (NRF24L01 2.4GHz)	Transmits and receives signals.
6DoF IMU (MPU-6050)	Captures information due to movement.
Vibration Motor	Provides the user a haptic feedback indicating that the OAR is near an obstacle.

2.2 are used to build the SH.

3.1 Inertial Measurement Unit

This inertial unit measures the acceleration and angular velocity composed of three accelerometers and three gyroscopes. Estimating acceleration and angular velocity maybe not too trivial since an accelerometer provides an acceleration measurement and a gyroscope provides an angular velocity measurement. On the one hand, the tilt angle θ_{acc} is derived from a_z and a_y as follows:

$$\theta_{acc\,x,y} = \arctan(\frac{a_{x,y}}{a_z}). \tag{9}$$

It then passes through a low-pass filter to eliminate all high frequency noise, leaving a static or slowly changing value for θ_{acc}. On the other hand, the gyro result is integrated to give θ_{gyro} as follows:

$$\theta_{gyro\,x,y} = \int \dot{\theta}_{gyro\,x,y} dt. \tag{10}$$

A high-pass filter is used to reduce signal drift of the angle computed by the gyroscope. The two signals are weighted and then summed, which gives us a filtered measurement without any drift. The weighting factors are constants(the weights used for this project are 0.7 for the gyroscope with a complement of 0.3 for the accelerometer). The concept of the complementary filter illustrated in the Figure 5. This type of fusion assumes that the performance of the sensors does not change over time and does not suffer from temporary outbreaks of significant interference.

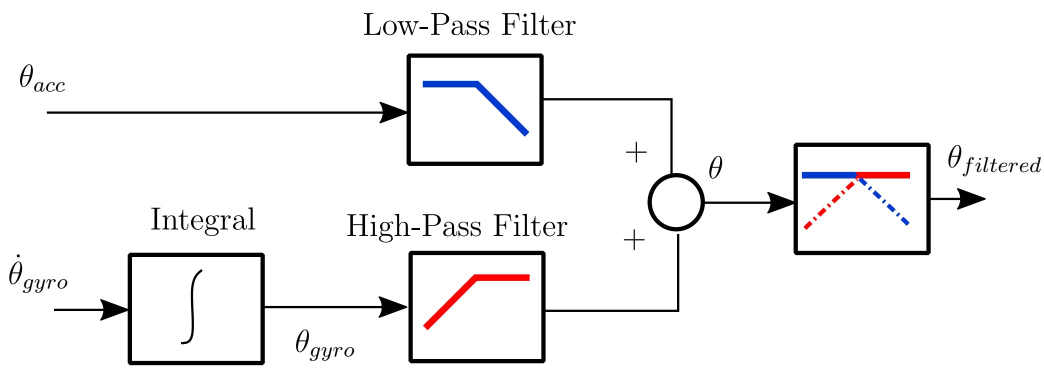

Figure 5: Complementary Filter. [7]

This motivates the following experiment: We concatenate the Kalman filter after the complementary filter, since the Kalman filter that can adapt to changing noise conditions that reduce the weight given to a sensor if its result is very noisy. Figure 6 shows the results. Surprisingly,

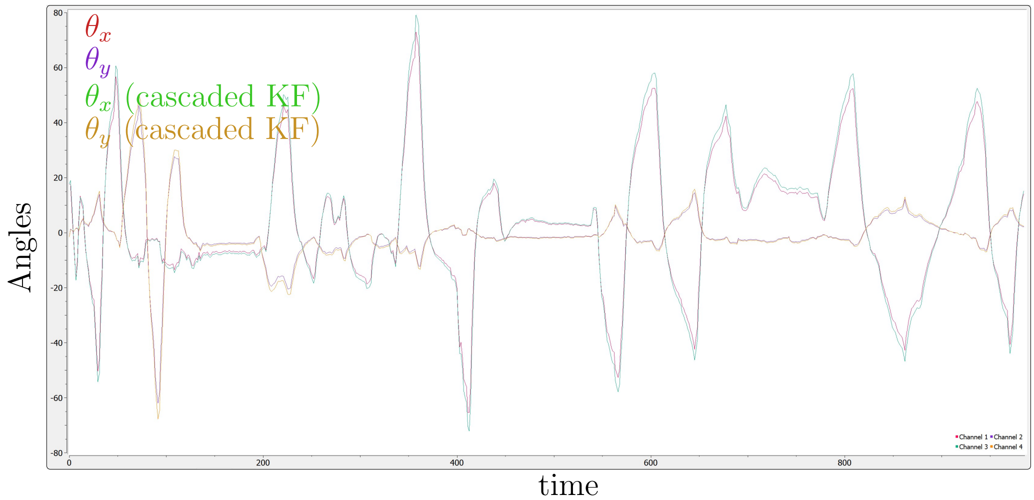

Figure 6: Complementary filter vs. cascading of the complementary and the Kalman filter.

the Kalman filter did not add a high improvement, therefore we limited the implementation to the complementary filter in order to reduce the computational cost.

3.2 Vibration Motor

The vibration motor is turned on if the OAR observes an obstacle in its range.

4 The Overall System

The idea of the project is to control a robot using hand-gestures. The working of the system is described as follows:

The user rotates his hand along the roll and the pitch axis. This rotation will be then captured by the IMU and sent through the Radio channel to the robot. The robot reads the values and converts them to duty-cycles of the driving PWM-signal allowing the variation of the speed of the wheels and hence its velocity. If an obstacles is observed within the range of the robot, a pulse is sent back to the user and the vibration motor is turned on. The robot will not further move in the direction of the obstacle. The user will now try to move the robot in another direction.

5 Conclusion

We conclude that this project has provided us with a very interesting and rewarding experience. In addition, we have successfully implemented the important concepts in electronics, mechanics, robotics and computer science seen during our lecture, trying to integrate the features we needed to make our robot functional. Experiments regarding integrating the Kalman filter showed an improvement of the accuracy. However, the complementary filter was good enough to get accurate estimations of the inertial data.

References

[1] ELEC Freaks, "Ultrasonic Ranging Module HC - SR04 ".

[2] ATmega328P datasheet - Atmel.

[3] nRF24L01 Single chip 2.4 GHz Transceiver - NORDIC.

[4] Ultraschall Messmodul HC-SR04 - KT-elektronic.

[5] DUAL FULL-BRIDGE DRIVER L298 - Sparkfun.

[6] Scalar Kalman Filter - http://140.113.144.123/EnD98/Unit

[7] DESIGN AND IMPLEMENTATION OF HOME USE PORTABLE SMART ELECTRONICS.