Adaptive Bayesian Filter Implemented in FPGA for Performance Improvement of Low-Cost Sensors

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***Abstract*:** Distance sensors are commonly used for obstacle detection and distance measurement, providing information for various applications such as collision prevention, object detection, and terrain mapping. However, they exhibit a wide range of quality and accuracy, with prices ranging from USD 0.55 to over USD 100 per unit. Choosing the lowest-priced sensors directly impacts the reliability of the measurements, as noise levels in the measured values can be significant. This project aims to present an adaptive Bayesian filter model as a *proof of concept* to improve the reliability of measurements from low-cost sensors.

Keywords: ultrasonic sensor, Bayesian filter, low cost, adaptive filter.

1 INTRODUCTION

The developed project aims to present a *proof of concept* for the application of a Bayesian Filter in FPGA to enhance the reliability of measurements taken by the HC-SR04 ultrasonic sensor. The prototype is built by assembling a circuit using the VHDL hardware description language and Intel Quartus Prime, which implements the solution proposed in (1), with necessary and convenient adaptations for the FPGA project. The model is based on a series of Bayesian networks (or Hidden Markov Chains).

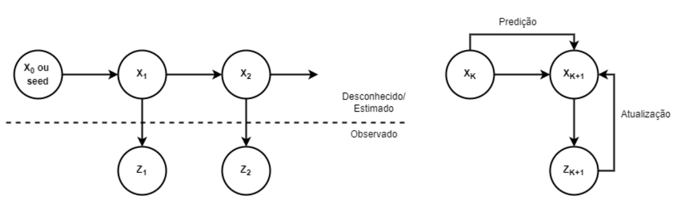

Figure 1: Bayesian Network Model (left) and Prediction and Update Model (right).

The processed measurement values in the circuit are represented in single-precision floating point format according to IEEE 754 standards.

2 TECHNICAL SOLUTION

In this project, floating-point calculation modules (IEEE 754) were developed to implement the Bayesian filter in hardware, a module for converting the sensor measurements to floating point, and a module for controlling the adaptation of the Bayesian filter. The calculation module was responsible for implementing the main expressions that make up the Bayesian filter (described in (1)), which will be presented below:

$$k_{k|1} = \left(\frac{\sigma_k^2 + \sigma_p^2}{\sigma_m^2 + \sigma_p^2 + \sigma_k^2} \right) \tag{1}$$

$$\sigma_{k|1}^2 = (1 - k_{k|1})(\sigma_k^2 + \sigma_p^2) \tag{2}$$

$$x_{k|1} = k_k z_{k|1} + (1 - k_{k|1}) x_k \tag{3}$$

With the following initial conditions:

$$k = \left(\frac{\sigma_0^2 + \sigma_p^2}{\sigma_m^2 + \sigma_p^2 + \sigma_0^2} \right) \tag{4}$$

$$\sigma_1^2 = (1 - k_1)(\sigma_0^2 + \sigma_p^2) \tag{5}$$

$$x_1 = k_1 z_1 + (1 - k_1) x_0 \tag{6}$$

Let x_0 be a seed value and σ_0^2 an arbitrary value to start the iterations. The outputs or estimates of the model, denoted by $x_{k|1}$, are given by $X_1 = X_0 + \epsilon_P$ with $\epsilon_P \rightarrow N(0, \sigma_p^2)$. In turn, the measured distances are represented by the true measured value with added uncertainty given by σ_m^2.

The development of these calculation components and the conversion of the sensor signal, specifically the floating-point arithmetic components, was supported by the libraries available in the Intel Quartus development software – IP Catalog.

The circuit is capable of performing distance measurements from the ultrasonic sensor, executing the Bayesian filter calculations, and transmitting both the measured and filtered data to a Python-based notebook interface via serial communication and MQTT protocol. Finally, the adaptive control module allows adjustments to the sensor parameters, altering the sensitivity of the filtering.

3 RESULTS AND DISCUSSION

Through the proposed solution, it was possible to obtain very satisfactory results, achieving different operational conditions of the filter in which the adaptation to the environment is variable. Three distinct filtering tests will be presented. Figures 2 and 3 show tests with fixed parameters. In Figure 4, the filtering performed is the result of the automatic adaptation of the circuit, as shown in Table 2.

1. **Case 1:** $\sigma_p = 0.01$ **e** $\sigma_m = 0.25$

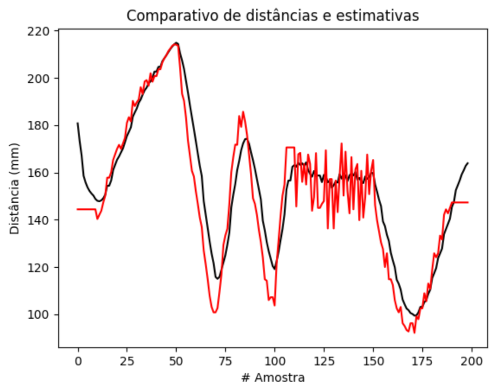

Figure 2: Output Comparison for the Circuit **with filter** and without filter.

2. **Case 2:** $\sigma_p = 0.05$ **e** $\sigma_m = 0.5$

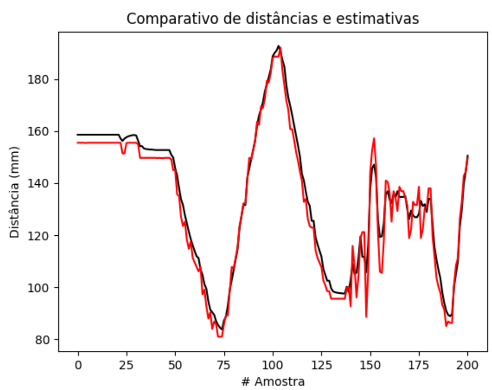

Figure 3: Output Comparison for the Circuit **with filter** and without filter.

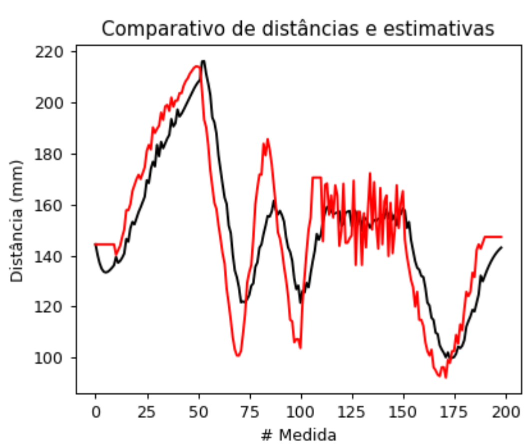

Figure 4: Output Comparison for the Circuit **with filter** and without filter - Adaptive Circuit.

Thus, the following variances were obtained, where the *real variance* represents the measurements from the standard circuit and the *estimated variance* represents the measurements from the circuit with the filter applied.

Cases	Measured Variance (mm^2)	Estimated Variance (mm^2)
Case 1	926.11	780.54
Case 2	732.69	713.32
Case 3 - Adaptation	926.11	694.80

Table 1: Comparison of variances between the measured and estimated curves.

Intervals (Accel in unit U)	σ_P	σ_M	Address
Acel $>$ 10	0.01	0.6	000
7 $<$ Acel $<$ 10	0.05	0.6	001
3 $<$ Acel $<$ 7	0.08	0.58	010
0 $<$ Acel $<$ 3	0.1	0.55	011

Table 2: Addressing relation of the parameters.

The filtering parameters of the Bayesian network yield different results depending on the sequence of measurements to be filtered. In Figure 3, for example, the good coupling between the curves in the measurement range from 0 to 125 results in ineffective noise filtering for the range from 130 to 180. The adaptive filtering model is an alternative to improve noise filtering. In Table 1, the first and third rows show the results of filtering the same set of measurements. The variance obtained with the adaptive model was lower, indicating preliminary better filtering. However, in this case, the lower variance resulted in a worse coupling between the curves, as seen in Figures 2 and 4.

4 CONCLUSION

The developed project successfully validated the performance of the adaptive filtering circuit, which employs a Bayesian filter in hardware to enhance output accuracy. Determining the parameter table proved to be a highly challenging task, as the filtering process is indirectly influenced by both the shape of the curve (the sequence of measurements) and the magnitude of the measured data.

Based on the tests conducted, the results of the presented proof of concept support the hypothesis that the model functions correctly. The acceptance of this hypothesis can be further validated through scaled testing and continued research in future studies.

5 REFERENCES

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