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Multi Sensor Cross Layer Integrity Framework: Concept For Information Reliability Assessment Of Safety Critical Systems

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The past few decades have seen an unprecedented rise in technological development, that led to exponentially increasing computational capabilities and the possibility of relying on complex sensor systems to automatically monitor safety-critical applications. These technological advancements have provided enormous advantages, but they are also responsible for an increased reliance on technology, raising the importance of assessing and improving the integrity of sensors that are ever more frequently used on various systems. Due to the multitude of systems that relies on the information provided by sensors, with various requirements and specific characteristics, the challenge of designing a standard solution capable of guaranteeing the integrity of a generic monitoring system is unmet. In the literature, it has been found specific solutions for specific problems, with most of the integrity monitoring methods devoted to positional integrity in the navigation domain (Costa de Oliveira et al., 2022; Jing et al., 2022). Considering this gap in the field, the development of a multi-sensor integrity monitoring strategy, flexible to work with different sensor types, and capable of meeting the integrity requirements for safety-critical scenarios, would be highly desirable. The concept proposed here is a step towards that realization.

The proposed Multi Sensor Cross Layer Integrity Framework considers that the sensor information can be encapsulated in different abstraction layers, with the raw measurements in the lower layer, and processed and combined results in the higher ones. The hypothesis being investigated is that this layered representation can improve the integrity of multi-sensor solutions, and the overall resilience of the system being monitored by those sensors. The use of abstraction layers to organize information has been used in various fields and applications, being particularly useful for developing models of processes and or systems (Benjamin et al., 1998). Inspired by that concept, the information provided by the sensors, as well as the appropriate fault detection steps related to each information, was divided into three layers as follows:

- Layer I: information on the sensor level, including the physical data acquisition and the raw measurements provided by each sensor in its unaltered, unprocessed form;
- Layer II: additional intelligence, relevant for the specific application, is extracted from the sensor measurements using appropriate data processing, models and algorithms;
- Layer III: information aggregation, or fusion, for decision-making support, combining the intelligence gathered by various sensors, historical data and/or the specific application context.

The proposed framework, summarized in the Figure 1 (a) diagram, uses multiple fault detection (FD) steps to estimate the confidence of the information provided by each sensor under various conditions. The method considers the influence of external conditions and the integrity of sensor information in previous layers to calibrate the fault detection results.

For each sensor, processing or fusion step, the appropriate state-of-the-art FD methods could be used. The output of these various detection steps can be standardized as a probability value associated with the occurrence of a certain fault scenario. In this way, a FD step can be seen as a classification model, yielding a predicted confidence level for a fault class. Ideally, that confidence value would match the observed empirical accuracy of detecting that fault mode. However, a classification model would always have some calibration error, that can be visualized in a reliability diagram, as shown in Figure 1 (b). That error is typically represented as the expected calibration error (ECE) metric (Naeini et al., 2015). Considering that different conditions affects the calibration curve, and that fault scenarios for the sensor information at different abstraction layers could characterize particular scenarios, we propose a cross-layer condition-based calibration adjustment of the fault detection results. Temperature-scaling techniques have been proposed to improve the calibration of machine learning classifiers (Joy et al., 2023). A similar approach would be implemented in the proposed framework to improve the integrity of complex multi-sensor systems. The method requires historical data of the system under the various conditions being considered. However, through a Bayesian inference process, the calibration parameters can be estimated with limited data.

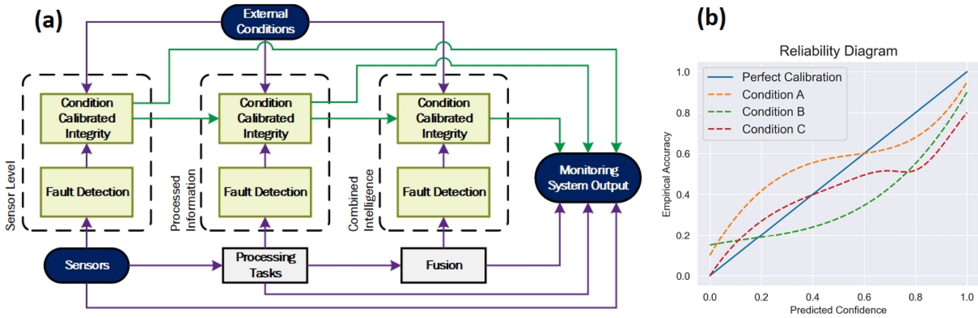

Fig. 1. (a) Multi-sensor cross-layer integrity framework representation; (b) Example of different conditions affecting the calibration curve.

This method could be implemented in any safety critical scenario that requires reliable information from multiple sensors. However, to demonstrate the cross-layer concept, an example that contains different types of sensors, with processing and fusion steps, is required. The perception system in an autonomous ship was selected for that reason. Autonomous ships require high situational awareness provided by a variety of different sensors, and the integrity of the information provided by those sensors is key for a safe and effective navigation. Although there can be different arrangements of sensors for an autonomous ship monitoring solution, a possible design includes a combination of cameras, radar, LiDAR, acoustic sensors, and a navigation unit (Thombre et al., 2022). A simplified version of that system, including only one camera, a LiDAR and a GNSS/INS position sensor, will be considered. The continuation of this work involves the simulation of typical fault scenarios for that system, and the development of an environment to evaluate the performance of the proposed framework. In the future, the method will be tested in a real small-scale autonomous vessel model, featuring the aforementioned sensors.

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References

Costa de Oliveira, F. A., Sill Torres, F., Garcia-Ortiz, A. 2022. Recent advances in sensor integrity monitoring methods-A review. IEEE Sensors Journal 22(11), 10256-10279.

Jing, H., Gao, Y., Shahbeigi, S. Dianati, M. 2022. Integrity Monitoring of GNSS/INS Based Positioning Systems for Autonomous Vehicles: State-of-the-Art and Open Challenges. IEEE Trans. on Intelligent Transportation Systems 23(9), 14166-14187.

Benjamin, P., Erraguntla, M., Delen, D., Mayer, R. 1998. Simulation modeling at multiple levels of abstraction. Winter Simulation Conference 1, 391-398.

Naeini, M.P., Cooper, G.F., Hauskrecht, M. 2015. Obtaining well calibrated probabilities using bayesian binning. Proceedings of the Twenty-Ninth AAAI Conference on Artificial Intelligence (AAAI'15), 2901-2907.

Joy, T., Pinto, F., Lim, S.N., Torr, P.H.S., Dokania, P.K. 2023. Sample-dependent adaptive temperature scaling for improved calibration. Proceedings of the Thirty-Seventh AAAI Conference on Artificial Intelligence 37, 14919-14926.

Thombre, S., Zhao, Z., Ramm-Schmidt, H., Vallet García, J.M., Malkamäki, T. et al. 2022. Sensors and AI techniques for situational awareness in autonomous ships: A review. IEEE Transactions on Intelligent Transportation Systems 23(1), 64-83.