Evaluation Framework for Performance Limitation of Autonomous Systems under Sensor Attack

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Abstract. Autonomous systems such as self-driving cars rely on sensors to perceive the surrounding world. Measures must be taken against attacks on sensors, which have been a hot topic in the last few years. For that goal one must first evaluate how sensor attacks affect the system, i.e. which part or whole of the system will fail if some of the built-in sensors are compromised, or will keep safe, etc. Among the relevant safety standards, ISO/PAS 21448 addresses the safety of road vehicles taking into account the performance limitations of sensors, but leaves security aspects out of scope. On the other hand, ISO/SAE 21434 addresses the security perspective during the development process of vehicular systems, but not specific threats such as sensor attacks. As a result the safety of autonomous systems under sensor attack is yet to be addressed. In this paper we propose a framework that combines safety analysis for scenario identification, and scenario-based simulation with sensor attack models embedded. Given an autonomous system model, we identify hazard scenarios caused by sensor attacks, and evaluate the performance limitations in the scenarios. We report on a prototype simulator for autonomous vehicles with radar, cameras and LiDAR along with attack models against the sensors. Our experiments show that our framework can evaluate how the system safety changes as parameters of the attacks and the sensors vary.

Keywords: Autonomous systems · Safety · Security · Sensor attack · SOTIF · Performance limitation · STAMP/STPA

1 Introduction

Autonomous systems such as autonomous vehicles rely on various sensors to perceive the surrounding world and decide what to do next. There have been a lot of reports on attacks against sensors, e.g. magnetic wheel speed sensors [32], gyro sensors [33], FMCW radar [32], and LiDAR [31,28], and against sensor-based autonomous systems [21]. The safety of autonomous systems against sensor...
attacks must therefore be assured. As an illustrative example, we use AEB-equipped cars with radar, cameras and LiDAR (Fig. 1) throughout the paper. AEB (Autonomous Emergency Braking) uses the sensors to detect objects around the car, and measure the distance to and relative speed of the nearest one in front. If it detects an impending crash, it will dispatch a warning or apply braking. There is high risk of serious accidents if the sensors are compromised.

To assure the safety of autonomous systems, scenario-based simulation \cite{37,19} is widely accepted as a key tool because real-world testing for hundreds of millions of miles \cite{18} is unrealistic. One of the issues of scenario-based simulations is how to select a set of relevant scenarios from the vast space of scenarios consisting of many parameters. The issue, of course, applies to sensor attack evaluation as well. In addition, to evaluate the effect of sensor attacks on autonomous systems, we need autonomous system simulators that embed sensor attack models, but there has been none thus far.

In this paper we propose a framework to evaluate performance limitations of autonomous systems in the light of SOTIF. It combines STAMP/STPA-based safety analysis to identify sensor attack scenarios to be evaluated, and sensor attack simulation to evaluate the effect of sensor attacks in the scenarios. We elaborate on safety analysis steps and results for AEB-equipped cars, and provide a prototype of a sensor attack simulator and examples of evaluation using it.

**Contributions** The main contributions of this paper are threefold:

- Evaluation framework of performance limitations that combines safety analysis and sensor attack simulation (Section 2).
- Method of attack scenario identification based on STAMP/STPA safety analysis together with concrete results for AEB (Section 3).
- Autonomous system simulator with sensor attack models embedded, and a prototype for AEB together with evaluation examples (Section 4).
2 Evaluation Framework Based on SOTIF Process

2.1 Relevant standards and SOTIF

ISO 26262 [14] and ISO/PAS 21448 [15] are safety standards for road vehicles. The former addresses functional safety as the absence of unreasonable risks caused by failures; The latter complements functional safety, addressing SOTIF (Safety Of The Intended Functionality) as the absence of unreasonable risks due to intended functionality or performance limitation. SOTIF takes into account sensors that advanced functionalities these days rely on. ISO/SAE 21434 [16] addresses the security aspects of road vehicles. It focuses on security risk management during the development process, and specific attacks are out of scope.

The notion of performance limitation in SOTIF with sensors in mind is compatible with evaluating how sensor attacks affect the system, more specifically, which part or whole of the system will fail if some of the built-in sensors are compromised, or will keep safe nevertheless, etc. We therefore construct an evaluation framework based on the improvement process of SOTIF (Fig. 2).

![Fig. 2. SOTIF improvement process](image)

Fig. 2 depicts a cycle process in which Functional and System Specification is the starting point, hazard scenarios are identified for it, and functions are modified to mitigate the hazard factors. Performance requirements for sensors are thereby defined at the design stage. On the other hand, model-based design is widely accepted for autonomous systems such as vehicles and robots. It helps evaluate and improve the specification in a continuous manner from the early stages of development by using an executable specification that can be simulated, called a model, throughout development. We adopt a model-based design framework.

2.2 Evaluation Framework

We present an evaluation framework for performance limitation under sensor attacks (Fig. 3). The framework is a combination of STAMP/STPA-based safety analysis for identifying sensor attack scenarios (Section 3), and sensor attack simulation for evaluating the performance limitations in the scenarios (Section 4).
In our framework, the starting point is Autonomous System Model, the model of the target autonomous system that is created by model-based design. Given a system model, we extract a control and feedback structure from it to be analyzed by the left side of the framework. Once attack scenarios have been identified by the analysis, we revert the scenarios to the right side of the framework to be evaluated by sensor attack simulation.

3 Identifying Attack Scenarios Using STAMP/STPA

3.1 STAMP/STPA Safety Analysis

In general, safety analysis is used to identify scenarios that can lead to hazards. Examples of safety analysis methods include FTA (Fault Tree Analysis) [10], FMEA (Failure Mode and Effect Analysis) [11], and STAMP/STPA [20]. While FTA and FMEA focus on hazards caused by component failures, STAMP/STPA takes the view that hazards can also occur as a result of unintended interactions between components even if none of them has any failure. The view is compatible with SOTIF, and we therefore use STAMP/STPA.

3.2 Analysis Steps and Results

We extract a control and feedback structure to be analyzed from the target system model. Fig. 4 shows the extracted structure, which consists of the fewest components possible for brevity, e.g. sensors are not separated from AEB ECU. The labels at the bottom indicate the correspondence to Fig. 6.

STAMP (Systems Theoretic Accident Model and Processes) is an accident causality model based on system theory, which underpins the analysis method STPA (System-Theoretic Process Analysis).
Safety Constraints STAMP/STPA first defines hazards that can lead to losses (e.g., injury, a loss of life, etc.), and safety constraints as the inverse of hazards. Safety constraints thereby specify the conditions to be satisfied to keep the system safe, and we therefore use them as evaluation criteria for performance limitation. For the current example, we define five safety constraints, one of which is the following: \textit{SC1: When the nearest object in front is within a defined distance, brake must be applied within a defined period of time to decelerate and stop the ego vehicle.} We refer to it as \textit{SC1} and use it as an example.

Unsafe Control Actions The next step is to identify UCAs (Unsafe Control Actions) that can break the safety constraints. STAMP/STPA offers a systematic method for it by categorizing the causal relationship between control actions and hazards into four types: 1) providing, 2) not providing, 3) too early, too late, and 4) stopped too soon, applied too long. For the current example, we identify 21 UCAs in total, 14 of which are related to AEB.

Hazard Scenarios The final step of STAMP/STPA is to identify hazard scenarios based on the UCAs. To create scenarios in a systematic manner, we use hint words supported by STAMP Workbench \cite{12}, e.g. 1) Control input or external information wrong or missing, 2) Inadequate or missing feedback, Feedback Delays, etc. We identify 15 scenarios for the current example.

Attack Scenarios We create attack scenarios from hazard scenarios by linking sensor attacks to the causes of hazards. For that purpose we gather a list of sensor attacks from existing works that are relevant to AEB-equipped vehicles with radar, cameras and LiDAR. For radar, we consider denial jamming that prevents object detection \cite{35,21}, and deception jamming on the range \cite{6,35,26,7,21} and on the velocity \cite{35}; For cameras, adversarial patches \cite{36} that disturb the object detection algorithm; For LiDAR, blinding attacks \cite{31} that perturb the measuring light. We categorize the attacks into 11 types according to the events that they cause, and thereby are able to link the attacks to the hazard scenarios.
We identify 102 attack scenarios in total for the current example. Fig. [5] shows example scenarios that can break SC1. The scenarios are yet to be concretized for use by the sensor attack simulator; They are later embedded in operational scenarios (see Fig. 10).

4 Evaluating Performance Limitations under Sensor Attacks

We present a sensor attack simulator to realize the right side of the framework (Fig. 3). The top-level structure is shown in Fig. 6. Given the safety constraints
and attack scenarios, it evaluates the performance limitations of the target autonomous system by testing if the system satisfies the safety constraints in the attack scenarios. We choose MATLAB [22]/Simulink [23] as a platform widely used in model-based design together with Unreal Engine [9] to implement the external environment and its boundaries with sensors and attacks.

We build a prototype of a sensor attack simulator for an AEB-equipped car with radar, cameras and LiDAR.

4.1 Verification of Safety Constraints

The simulator must check if the target system satisfies the safety constraints, and if not, stop running. There are largely two methods for such evaluation: conventional testing and formal verification. They have their merits and demerits, and do not exclude but complement each other [5,17]. For example, formal verification can give a proof for the verification result by checking all possible states, while it can also lead to state explosion as the complexity of a system increases. One usage is therefore to formally verify the safety-critical part of the system and to test the system as a whole in a conventional way. In this paper we use a conventional testing method with the focus on evaluating the safety of the autonomous system as a whole.

For the current example of AEB, the safety constraint $SC1$ states that the AEB control is correct, which can be evaluated as follows: The target model maintains the positions and velocities of objects measured by sensors, and the AEB control calculated from them. It also maintains the true values of positions and velocities, and we can use them to calculate the true AEB control. By comparing the two AEB controls, we can evaluate if $SC1$ is met.

When we add a model for the evaluation to the simulator, it is desirable to keep the target system model as unchanged as possible. Simulink Test [24] has a mechanism called a test harness to separate the model for testing from the model under test. Fig. 7 shows the resultant test model for $SC1$ in our prototype. Implemented as a test harness, the test model refers to and copies from the target model, but never changes it.

![Fig. 7. Prototype model for testing the safety constraint $SC1$](image-url)
4.2 Sensor Attack Simulator

The main body of the sensor attack simulator consists of seven models described below. All but the Attack model are assumed to be created through the development of the target system.

**Plant, Controller, State Estimation** Those are the core of a control system. Our prototype is built around the vehicle dynamics (Plant), AEB controller (Controller and State Estimation) and other peripheral models provided by MathWorks.

**Sensor, Perception & Decision, Attack** Those are to be designed considering what types of sensor attacks we want to evaluate. In this paper we model sensor attacks at the same level of abstraction as sensors and external environment with the view to evaluating attacks on sensors on their own, on sensor fusion, and on signal processing.

Therefore, the Sensor model is designed to include sensor fusion as well as separate sensors, namely radar, cameras and LiDAR. Sensor fusion is further divided into two stages: detection concatenation and multi-object tracking. The Perception & Decision model is designed to include object detection algorithms CFAR (Constant False Alarm Rate) for the radar and YOLO (You Only Look Once) v2 [29] for the cameras. The Attack model considers those algorithms as well as the sensors on their own. The resulting models of Sensor, Perception & Decision and Attack are shown in Fig. 8.

![Diagram of Prototype models of Sensor, Perception & Decision and Attack](image)

**Fig. 8.** Prototype models of Sensor, Perception & Decision and Attack

Our collection of attack models are as described in Section 3.2. We model the gathered list of sensor attacks that are relevant to AEB-equipped vehicles with radar, cameras and LiDAR. We show examples of sensor attack simulation supported by the prototype in Fig. 9.
External Environment It models the external environment surrounding the target system, e.g., nearby objects, how they are perceived by the sensors, and the positional relationship between the target system and the other objects. It also defines the temporal development of the target system and the environment as operational scenarios.

Our prototype models the external environment that comply with the evaluation criteria of AEB in JNCAP [2] and Euro NCAP [1], and supports the complete set of operational scenarios: largely, five scenarios of car detection and 11 scenarios of pedestrian and cyclist detection, and a total of 278 scenarios with parameter variations. As an example, Fig. 10 shows the CPNO (Car-to-Pedestrian Nearside Obstructed) scenario in JNCAP, where the ego vehicle travels forward towards a pedestrian crossing its path from the nearside who is out of sight at first due to stationary vehicles in between.

Fig. 10 also shows an example attack scenario embedded in CPNO, in which denial jamming is applied from a fixed point in front with the attacker’s initial position and signal strength variable. Those attack settings are not specified in Fig. 5. Only when we determine the operation scenario and embed an attack scenario into it, can we concretize the attack settings.
4.3 Evaluation Examples Using the Prototype

We show three examples of evaluation using the prototype: one about attack parameters, and two about sensor design parameters. We use the attack scenario of denial jamming in CPNO (Fig. 10). For the sake of brevity, the simulation stops when the car crashes into the pedestrian instead of when the safety constraints such as $SC1$ are not met.

**Jamming Attack on the Radar** We evaluate the effect of jamming attack on the radar with respect to two parameters: the attacker’s position and signal strength. The other parameters are fixed: the velocity of the ego vehicle is 25 [km/h], and the signal strength of the ego vehicle, 10 [dBm]. The cameras and LiDAR are not used for AEB control for the sake of evaluating the radar alone.

Fig. 11 shows the results. Each element of the matrix denotes whether the car crashes into the pedestrian (Crash) or not (Safe). The result is as expected: the stronger the attacker’s signal is, or the nearer the attacker’s position is, the more likely the attack is to succeed. That proves the validity of the simulation.

![Fig. 11. Evaluation result with respect to radar jamming parameters. The detections by camera and LiDAR are not used for AEB control.](image)

**Detection Concatenation** As an example of sensor fusion, we evaluate the effect of concatenation of the radar and camera. The attacker’s position and signal strength are set to 30 [m] and 10 [dBm], and all the other conditions are the same. The LiDAR is not used for AEB control.

Fig. 12 shows the results. The leftmost part shows object detection by the radar, and the central part, footage of the front camera of the ego vehicle, in which the upper half is in the case of the radar alone, and the lower half, the concatenation of the radar and camera. Due to the jamming, it is only when the distance is close to 0 [m] that the radar detects the person in front; It is too late to avoid a crash with the radar alone, while the car is safely stopped with the concatenation thanks to detection by the camera. The comparison proves the effectiveness of the concatenation.
Multi-Object Tracking As a second example of sensor fusion, we evaluate the multi-object tracking algorithm. Simply put, the algorithm tracks objects by maintaining a list of object detections by multiple sensors. To exclude the effect of misdetections, the algorithm confirms the detection if the same object is detected at least M times out of N sensing periods. Therefore, the greater the ratio M/N is, the more accurate the detection becomes. If we increase N with a fixed ratio M/N, we expect to eliminate the effect of variance and further improve the accuracy, while the algorithm can become more susceptible to attacks due to the increased processing time.

We evaluate the effect of the design parameters M and N in the same attack settings as in Fig. 11. Fig. 13 shows the evaluation results for (M, N) = (2, 2) and (9, 12). Overall, (M, N) = (2, 2) is safer than (M, N) = (9, 12) because there are fewer crashes in the former case. However, there are also cases where the brake
is applied too soon, which can lead to an uncomfortable driving experience. We can evaluate this kind of trade-off with our simulator.

5 Related Work

Coverage by scenario-based simulation for autonomous systems has been extensively studied [37,19,39,27,34]. Coverage criteria and techniques to maximize it are investigated in [34]. Coverage maximizing techniques include automated generation of test scenarios by random numbers [30,27] and by search algorithms [4]. In [4], the authors consider critical test scenarios leading to failures, which looks suitable for performance limitation evaluation. For specific systems like AEB, we have some prior knowledge about scenarios. In [37], scenarios are defined in a systematic manner with six layers such as road, moving objects and environmental conditions. There are other challenges in scenario-based simulation [19]. Interface between various autonomous system models and simulation tools is a key issue considering autonomous systems becoming more and more complex.

There have been works on safety analysis of autonomous systems using STAMP/STPA [3][13]. While we use conventional testing in this paper, formal methods are promising for verifying the safety constraints [3,8]. In [3], the authors embed the safety constraints to the target model, and formally verify them. A comparison with FTA is detailed in [13], which concludes that STAMP/STPA can identify more scenarios.

6 Conclusion

We present a framework to evaluate performance limitations of autonomous systems under sensor attacks. Using a prototype simulator of an AEB-equipped car with radar, cameras and LiDAR, we show that the framework can identify sensor attack scenarios to be assessed, and evaluate how attacks on the sensors affect the system safety.

Interface between different models and simulators is a key issue in evaluation of autonomous systems, especially when it comes to highly autonomous vehicles becoming more and more complex. We therefore leave it as future work to modularize the sensor attack models, e.g. as FMU (Functional Mock-up Unit), to be used in combination with other simulators. In addition to self-driving cars, there are a diverse range of critical devices and systems that depend on measurement, such as robotic systems, medical devices and control systems. We therefore want to extend our framework to address attacks and countermeasures about measurement interfaces in general: what is called instrumentation security.

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