Drift with Devil: Security of Multi-Sensor Fusion based Localization in High-Level Autonomous Driving under GPS Spoofing
(Extended Version)

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Abstract

For high-level Autonomous Vehicles (AV), localization is highly security and safety critical. One direct threat to it is GPS spoofing, but fortunately, AV systems today predominantly use Multi-Sensor Fusion (MSF) algorithms that are generally believed to have the potential to practically defeat GPS spoofing. However, no prior work has studied whether today’s MSF algorithms are indeed sufficiently secure under GPS spoofing, especially in AV settings. In this work, we perform the first study to fill this critical gap. As the first study, we focus on a production-grade MSF with both design and implementation level representativeness, and identify two AV-specific attack goals, off-road and wrong-way attacks.

To systematically understand the security property, we first analyze the upper-bound attack effectiveness, and discover a take-over effect that can fundamentally defeat the MSF design principle. We perform a cause analysis and find that such vulnerability only appears dynamically and non-deterministically. Leveraging this insight, we design FusionRipper, a novel and general attack that opportunistically captures and exploits take-over vulnerabilities. We evaluate it on 6 real-world sensor traces, and find that FusionRipper can achieve at least 97% and 91.3% success rates in all traces for off-road and wrong-way attacks respectively. We also find that it is highly robust to practical factors such as spoofing inaccuracies. To improve the practicality, we further design an offline method that can effectively identify attack parameters with over 80% average success rates for both attack goals, with the cost of at most half a day. We also discuss promising defense directions.

1 Introduction

Today, various companies are developing high-level self-driving cars [1] such as Level-4 Autonomous Vehicles (AV) [2], and some of them are already providing services on public roads such as self-driving taxi from Google’s Waymo One [3] and self-driving trucks from TuSimple [4]. To enable such high-level driving automation, the Autonomous Driving (AD) system in an AV needs to not only perform the perception of surrounding obstacles, but also centimeter-level localization of its own global positions on the map [5, 6]. Such localization function is highly security and safety critical in the AV context, since positioning errors can directly cause an AV to drive off road or onto a wrong way. Since in high-level AD systems the perception module is only designed for obstacle detection and the localization module is in full charge of identifying road deviations [7–11], even when the perception module is functioning perfectly, it cannot prevent a variety of road hazards specific to localization errors such as driving off road to hit road curbs, falling down the highway cliff, or being hit by other vehicles that fail to yield, especially when the AV is on the wrong way. However, recent security research in AD systems concentrates on AD perception, e.g., malicious stickers on traffic signs [12–15], which leaves the security of AD localization an open problem.

For outdoor localization in general, GPS is the de facto location source, and thus a direct threat to it is GPS spoofing, a long-existing but still unsolved security problem with practicality proven on a wide range of end systems [16–24], including low-autonomy AVs such as Tesla cars [22]. Fortunately, to achieve robust localization, real-world high-level AD systems today predominantly use Multi-Sensor Fusion (MSF) algorithms that combine GPS input with position inputs from other sensors, typically IMU (Inertial Measurement Unit) and LiDAR (Light Detection and Ranging) [7, 25–33]. Since in such design GPS input alone can not dictate the localization output, it is generally believed to have the potential to practically defeat GPS spoofing [18, 23, 34–37]. However, state-of-the-art MSF algorithms are mainly designed for improving accuracy and robustness, instead of security. This thus makes it largely unclear how secure they can be under GPS spoofing. Given its widespread use in AVs and high importance to road safety, it is thus imperative to systematically understand this as early as possible.

To fill this critical research gap, in this work we perform the first study on the security property of MSF-based localization in AV settings. As the very first study in this direction, we focus on GPS spoofing as the attack vector since it is one of the most mature attack vectors to the MSF input sources.
We focus on a production-grade MSF implementation, Baidu Apollo MSF (BA-MSF), due to its high representativeness in both design (KF-based MSF) and implementation (centimeter-level accuracy evaluated by real-world AV fleet). We consider the attack goal as using GPS spoofing to cause large lateral deviations in the MSF output, i.e., deviating to the left or right. This can cause the AV to drive off road or onto a wrong way, which we call off-road attack and wrong-way attack respectively.

To systematically understand the security property, we first analyze the upper-bound attack effectiveness via a dynamic blackbox analysis since BA-MSF is released in the binary form. We find that in the real-world trace, the majority (71%) of even such upper-bound attack results can only cause less than 50 cm deviation, which is far from causing either off-road or wrong-way attacks (need over 90 cm and 2.4 m respectively). This shows that MSF can indeed generally enhance the security against GPS spoofing. Interestingly, we also observe that there still exist a few upper-bound attack results that can cause over 2 meters deviations. For all of them, we find that GPS spoofing is able to cause exponential growths of deviations. This allows the spoofed GPS to become the dominating input source in the fusion process and eventually cause the MSF to reject other input sources, which thus fundamentally defeats the design principle of MSF. In this paper, we call it a take-over effect. We then perform a cause analysis and find that this only appears when the MSF is in relatively unconfident periods due to a combination of dynamic and non-deterministic real-world factors such as sensor noises and algorithm inaccuracies.

Such take-over vulnerabilities are highly attractive for attackers since they can exploit the exponential deviation growths to achieve arbitrary deviation goals. However, as discovered earlier, the vulnerable periods are created dynamically and non-deterministically. Thus, we design FusionRipper, a novel and general attack that opportunistically captures and exploits take-over vulnerabilities with 2 stages: (1) vulnerability profiling, which measures when vulnerable periods appear, and (2) aggressive spoofing, which performs exponential spoofing to exploit the take-over opportunity.

We implement FusionRipper and evaluate it on 6 real-world sensor traces from Apollo and the KAIST Complex Urban dataset. Our results show that when the attack can last 2 minutes, there always exists a set of attack parameters for FusionRipper to achieve at least 97% and 91.3% success rates in all traces for the off-road and wrong-way attacks respectively, with less than 35 seconds success time on average. To understand the attack practicality, we evaluate it with practical factors such as (1) spoofing inaccuracies, and (2) AD control taking effect, and find that for both cases the attack success rates are affected by less than 4%. Attack demos showing the end-to-end attack impact are available at https://sites.google.com/view/cav-sec/fusionripper.

In addition, we observe that the attack effectiveness is sensitive to the selection of the attack parameters. Thus, to improve the practicality, we further design an offline attack parameter profiling method that can collect effective parameters without causing obvious safety problems during such profiling to stay stealthy. Our results on real-world traces show that our method can effectively identify attack parameters with 84.2% and 80.7% success rates for off-road and wrong-way attacks respectively, with the profiling cost of at most half a day.

Considering the critical role of localization for safe and correct AV driving, the discovered attack against the state-of-the-art MSF algorithm requires immediate attention and defense discussion. To facilitate this, we also discuss both long-term and short-term defense directions.

In summary, this work makes the following contributions:

- We perform the first security study on MSF-based localization in high-level AV settings under GPS spoofing. We focus on a production-grade MSF with both design and implementation level representativeness, and identify two attack goals specific to the AV settings.
- We analyze the upper-bound attack effectiveness, and discover a take-over effect that can fundamentally defeat the MSF design principle. We further perform a cause analysis and find that such vulnerability only appears dynamically and non-deterministically.
- We design FusionRipper, a novel and general attack that opportunistically captures and exploits the take-over vulnerability we discover. We evaluate it on 6 real-world sensor traces, and find that it can achieve high effectiveness (over 97% and 91.3% success rates) for both off-road and wrong-way attacks. We also find that such high effectiveness is robust to various practical factors.
- To improve the attack practicality, we further design an offline attack parameter profiling method that can effectively identify attack parameters with 84.2% and 80.7% success rates for off-road and wrong-way attacks respectively, with the profiling cost of at most half a day. We also discuss promising defenses directions.

Details of this paper will be released after the responsible disclosure period.

References

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