ISCAS 中国科学院软件研究所学术年会暨重点实验室科技活动周 2025 第十届 学术论文

Testing the Fault-Tolerance of Multi-sensor Fusion Perception in Autonomous Driving Systems

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The 34th ACM SIGSOFT International Symposium on Software Testing and Analysis (**ISSTA 2025**)

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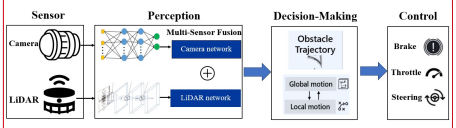
Background

Multi-Sensor Fusion (MSF) based Autonomous Driving System (ADS)



Core Components of Camera

Core Components of LiDAR

- Cameras capture high-resolution visual data, providing contextual information such as color, surface conditions.
- LiDAR uses laser beams to measure distances and generate high-precision 3D point clouds of the traffic environment, highly effective in accurately identifying the position and shape of objects.

Research Gap

Test the System-level Fault Tolerance of MSF-based Industrial ADSs

➢ **Generate adversarial examples or corner cases for the perception models to identify their errors in scenario understanding.**

- **Camera-based perception testing**: generate perturbations or patches to mislead deep learning-based camera models
- **LiDAR-based perception testing**: generate 3D adversarial point clouds to attack LiDAR-based perception models
- **MSF-based perception testing**: synthesize real-world data and seek to insert objects into scenarios to uncover perception errors in MSF-based modules, evaluating the perception accuracy under challenging scenarios

These approaches do not assess how perception errors propagate to subsequent modules or impact overall behavior of ADS.

➢ **Testing the Effects of Perception Errors or Sensor Faults on ADSs.**

- **Different LiDAR spoofing attack patterns** from previous studies to assess their impact beyond the perception stage and analyze their influence on the decision-making of ADSs
- **Inject camera faults into the perception and planning model** and test its planned trajectory output to find safety violations

Only targets camera-based ADS, disregarding the role of LiDAR and MSF in mitigating camera faults for ADSs

They do not verify whether the identified safety violations are genuinely caused by injected faults

Challenges

The first to test system-level fault tolerance of MSF-based ADSs, identifying behavioral safety violations caused by sensor faults

- **How to systematically and comprehensively model the sensor faults in real-world traffic**. The diverse and complex nature of traffic makes it difficult to comprehensively capture the unpredictable conditions affecting cameras and LiDAR on AVs.
- **How to identify system-level safety violations caused by injected sensor faults**. As the ADS is a highly coupled multi-component deep learning system, it is non-trivial to guarantee the discovered safety violations of ADS indeed arise from injected sensor faults.

Sensor Fault Models

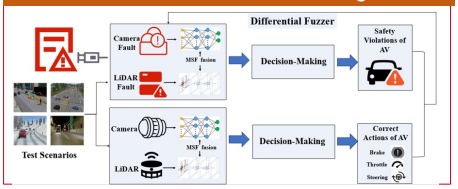
Camera Fault Models

Fault Category		Fault Type	An Example in Real Traffic	Faulty Componet
Component damage	Active Fault	Deflection	Due to bumpy roads, the camera deflects during AV driving	Camera Body
		Displacement	Due to bumpy roads, the camera is misaligned during AV driving	
		Internal Dirt	The dirt accumulation inside caused by driving outside or changing temperature for a long time	Len
		Broken Lens	The splashing foreign objects(e.g.,sand, gravel) hits the lens	
		Lens Brightness Change	Long-term usage in high-temperature or seaside cause brightness issues with basic components(e.g.,shutter,diaphragm,iris) of len	
		Blur	The blur introduced by malfunction of complex inside circuit	Image Sensor& ISP
Component undamage	Passive Fault	Internal Scatter	The color noise caused by malfunction of image signal processor	Len
		Lens Occlusion	The lens is covered with plastic bag or paper during AV driving	
		External Scatter	The surface of the camera's lens is contaminated with mud spots	
		Dust	The surface of the camera's lens is contaminated with dust	
		Raindrops	Raindrops appear on the lens along with rainlines during rainfall	
		Snow Grains	The deposit of snow grains on the lens during snowfall	
		Mist	Fogging of lens caused by high humidity and temperature differences	
		Ice	Temperature drops below zero degrees, resulting in ice on the lens	
		Overexposure	Under strong light sources such as high beams or reflective surfaces, camera receives too much light	Image Sensor
		White Balance Shift	At sunset, the camera image appears in red and orange tones due to white balance shift	Bayer Filter

LiDAR Fault Models

Fault Category		Fault Type	An Example in Real Traffic	Faulty Component
Component damage	Active Fault	Deflection	Due to bumpy roads, the orientation of LiDAR changes	LiDAR enclosure
		Displacement	Due to bumpy roads, the position of LiDAR is displaced	
		Beam Loss	Due to long-term wear&tear and aging, laser beam of LiDAR reduces	Emitter
		Line Fault	The noise caused by malfunction of internal circuits	Process-ing Unit
Component undamage	Passive Fault	Electromagnetic Interference	When AV passes airports or power plants,these areas will generate electromagnetic wave interference	Receiver
		Crosstalk	NPC vehicles using LiDAR drive around AV,and their emitted signals cause confusion to receiving channel of AV's LiDAR	
		Rain and Snow Pollution	There are foreign objects (such as rain, snow, mist, mud) covering LiDAR's surface,limiting the LiDAR's field of view	Scanner
		Strong Light Interference	The measurement distance and point-cloud density are reduced due to strong light occupying detector units	Process-ing Unit

Differential Fuzzer for Fault Tolerance Testing of ADSs

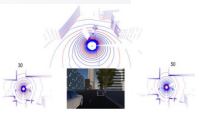


Experimental Results

Simulation Testing

Baidu 百度 | apollo

White Balance Shift



Beam Loss

Fault Type	Deflec-tion	Displace-ment	Broken Lens	Lens Bright-ness Change	Blur	Internal Scatter	Internal Dirt	Lens Occl-usion
Number of SVs	0.6	0.6	34.2	0.5	25	33.3	0.4	25.8
Fault Type	External Scatter	Overexpo-sure	Dust	Rain	Snow	Mist	Ice	White Bal-ance Shift
Number of SVs	24.9	28.1	1.8	10.2	22.6	0.2	2.7	9.4

Fault Type	Deflection	Displacement	Beam Loss	Line Fault
Number of SVs	95	90.6	60.8	51
Fault Type	Electromagnetic Interference	Crosstalk	Rain and Snow Pollution	Strong Light Interference
Number of SVs	87.4	78.6	85.8	65.7

Physical Experiments

Lens Occlu-sion		External Scatter		LiDAR Deflection		LiDAR Displacement		Strong Light to Camera and LiDAR	
min	50%	min	50%	min	70%	min	70%	min	80%
avg	60%	avg	62%	avg	82%	avg	80%	avg	92%
max	70%	max	70%	max	90%	max	90%	max	100%