Invisible Reflections: Leveraging Infrared Laser Reflections to Target Traffic Sign Perception

Takami Sato[*1], **Sri Hrushikesh Varma Bhupathiraju**[*2], Michael Clifford[3], Takeshi Sugawara[4], Qi Alfred Chen[1], and Sara Rampazzi[2]

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* denotes co-first authors.

Infrared (IR) laser is not visible to humans

To human eye
(normal camera with IR filter)

Infrared (IR) laser is not visible to humans

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To camera
without IR filter

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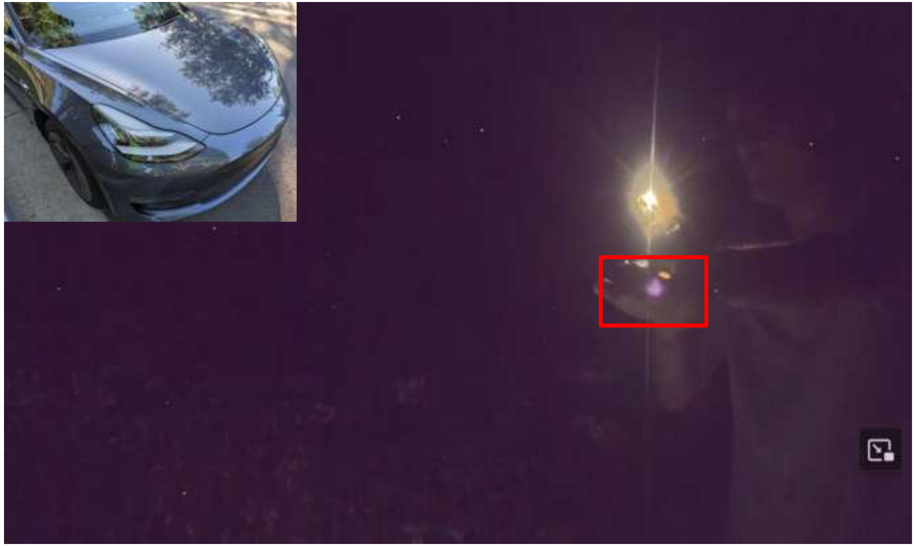
Can Infrared Laser Reflection (ILR) be a new attack vector?

Autonomous Vehicle Cameras without IR filters

ICSL (I Can See the Light) Attack [Wang et al., CCS'21]

- IR light is detected as red light

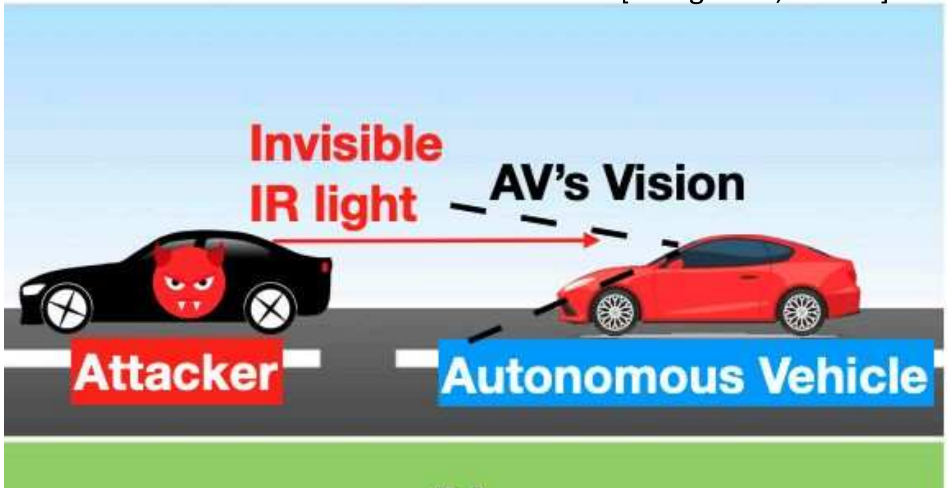


We also confirmed that a commodity car with AV does not have IR filter.

Limitations of Existing Attacks: Visibility for Human

ICSL (I Can See the Light) Attack

[Wang et al., CCS'21]



Patch Attacks

[Eykholt et al., 2018]

[Jia et al., 2022]

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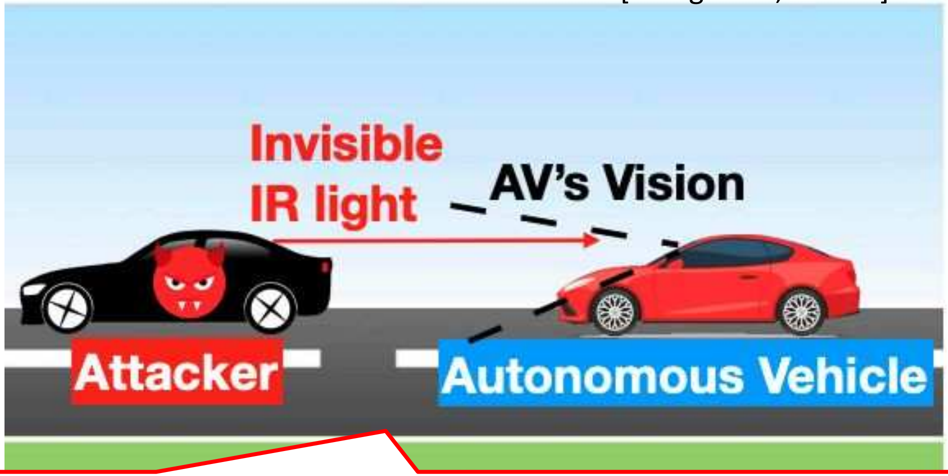

Limitation ①

- **Need accurate aiming at driving target**
- **Not designed for attacking traffic sign**

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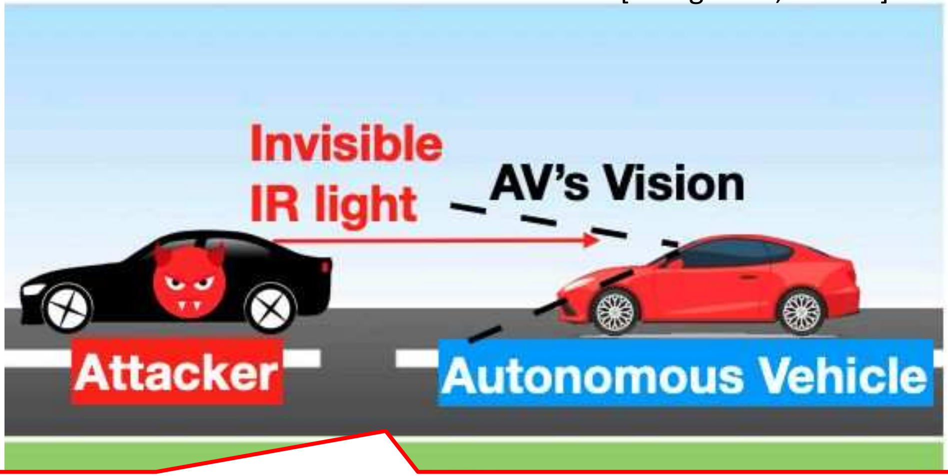

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Limitation ②

Attack attempt visible to human

Our Attack Vector: Infrared Laser Reflection (ILR)

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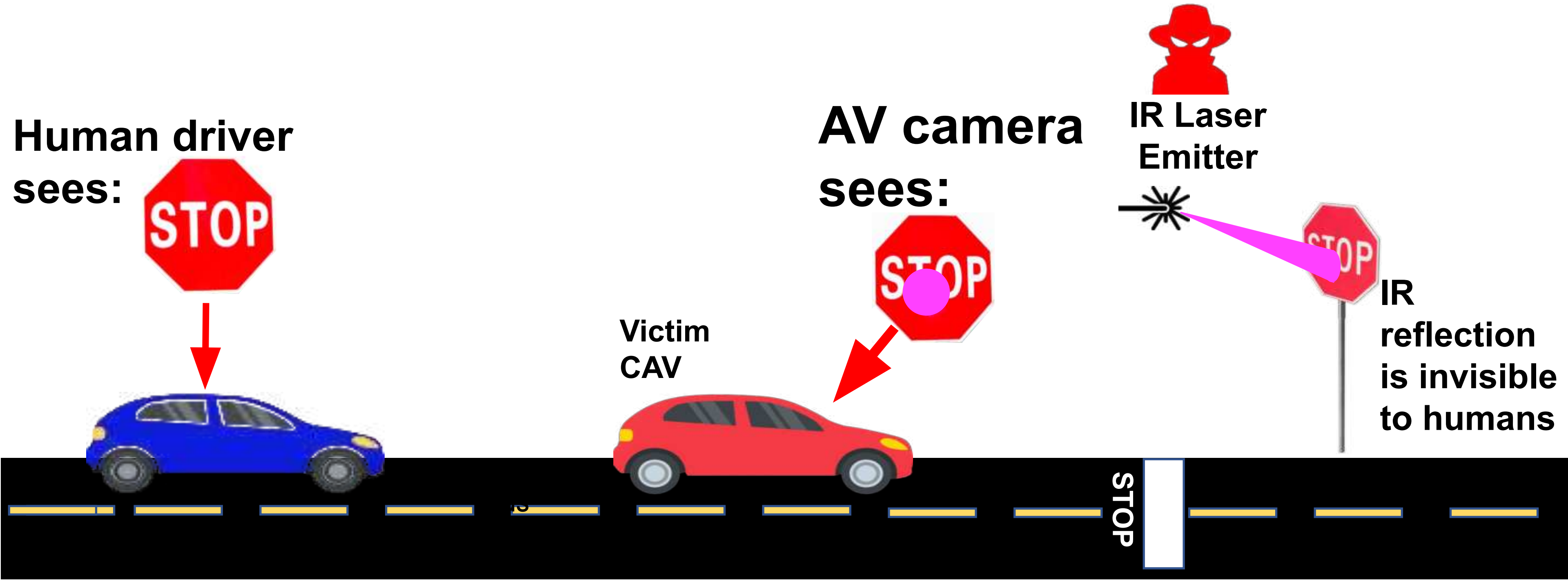

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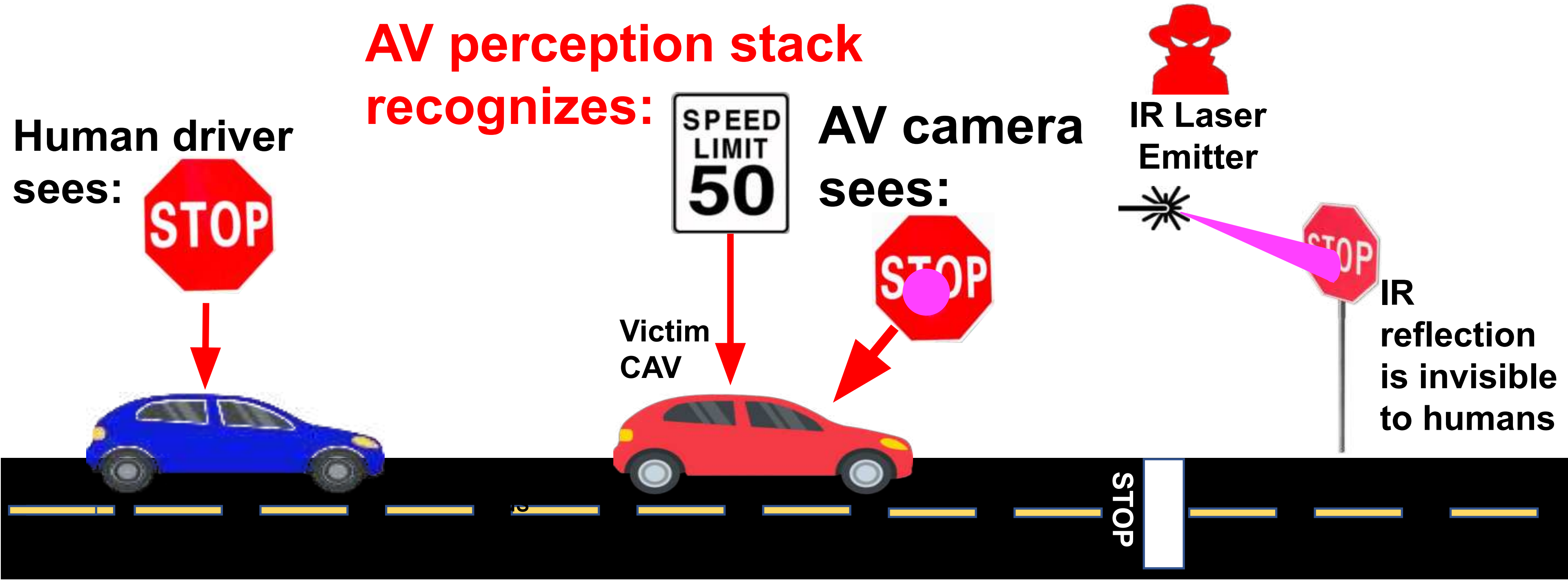
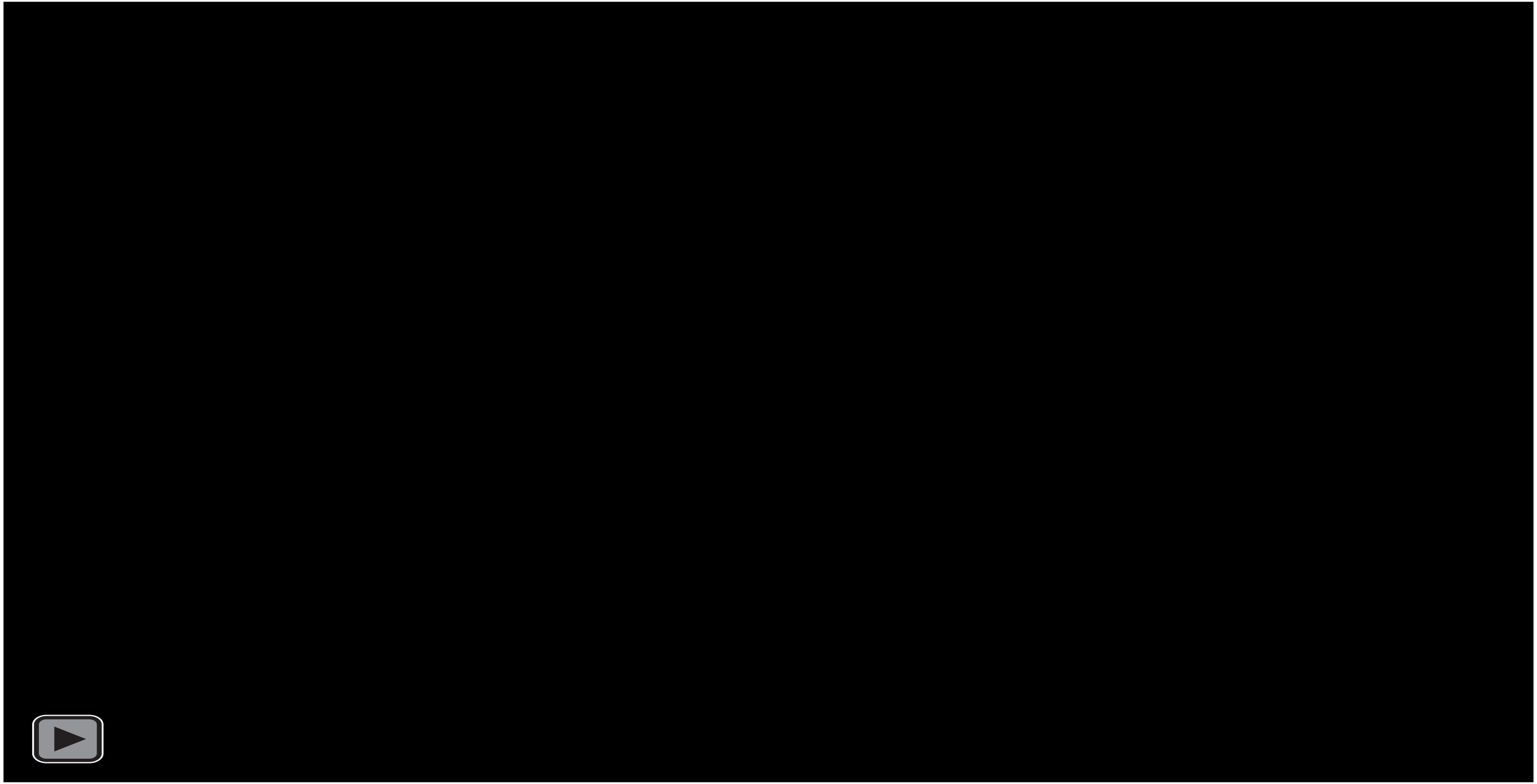


Attack Demo: Indoor Experiment



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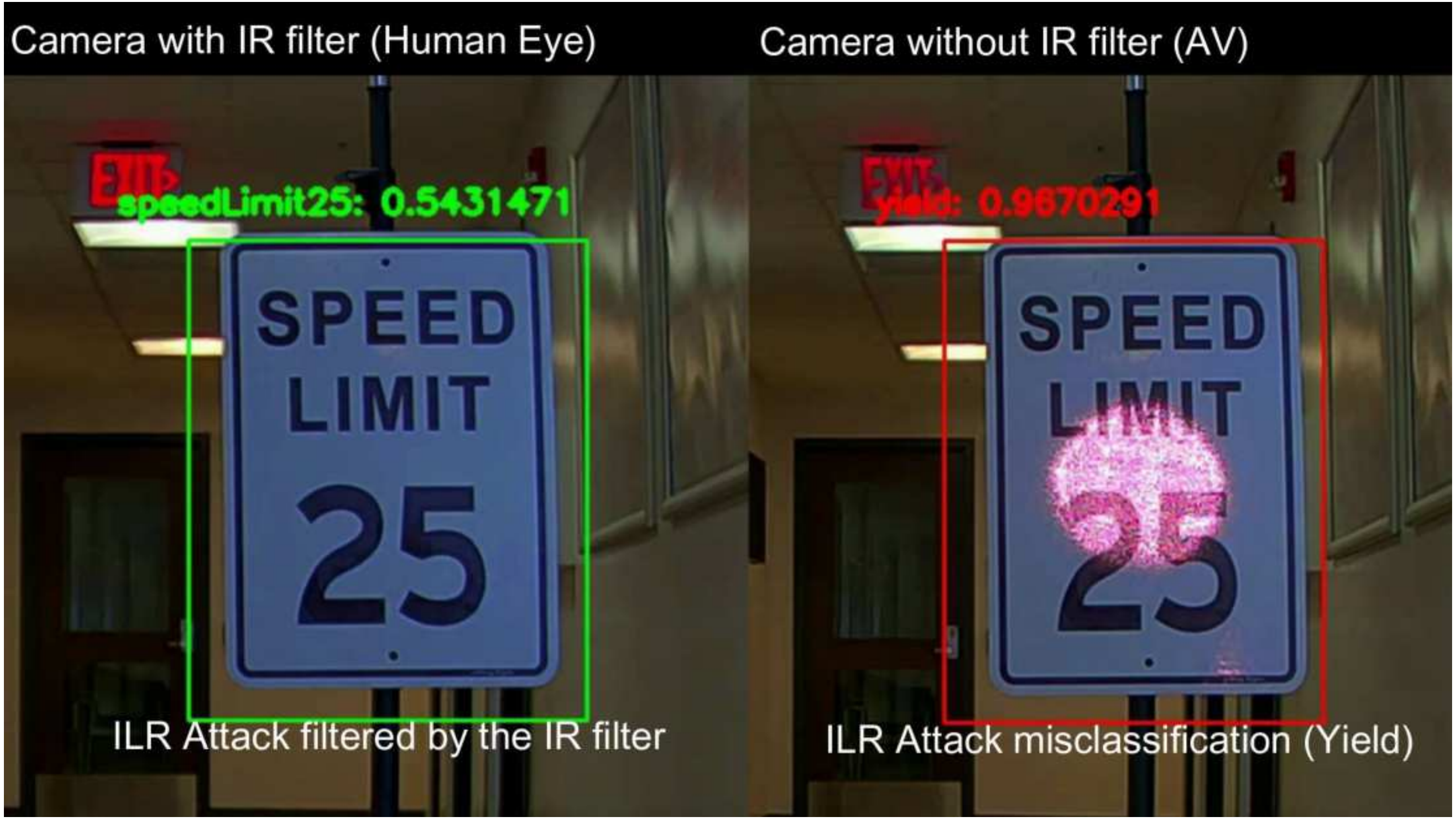
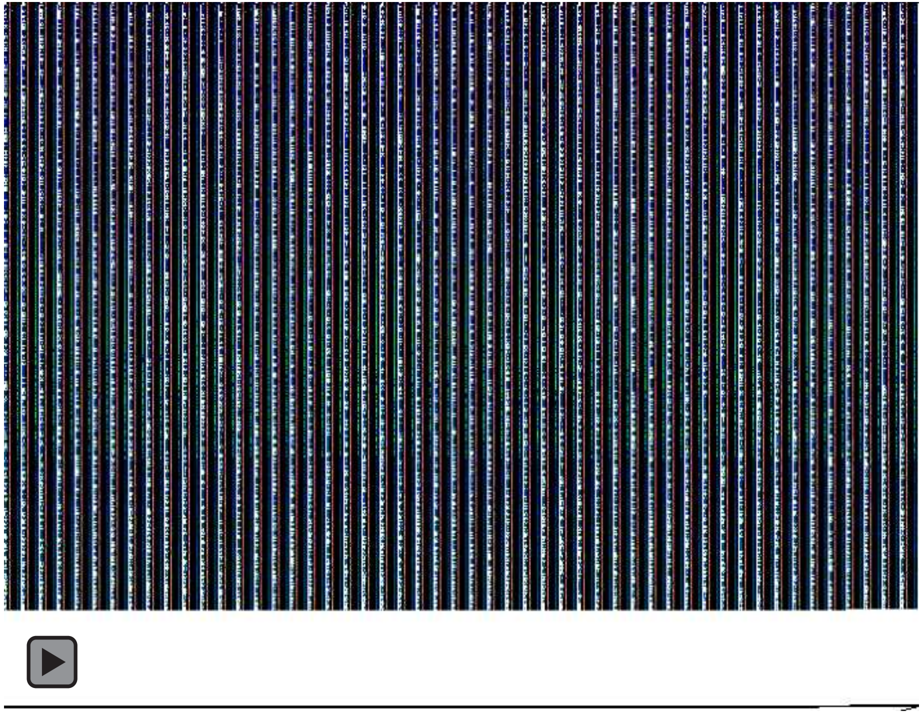


Attack Demo: Outdoor Experiment



Attack Demo: Outdoor Experiment

Research Challenges

- **<u>Physical attack capability understanding & modeling</u>**
  - Complicated physical process behind the speckle pattern
    - Pattern is generated from multiple, randomly phased, coherent waves
  - Non-trivial to effectively interpolate unseen ILR attack trace
    - Naive averaging cancels out the speckle pattern
- **<u>Automatic generation of effective attacks on traffic sign recognition model side</u>**
  - Attack effectiveness highly depends on the position, size, and intensity of the speckled pattern
  - Need to be robust to different distances and view angles

Naive trace modeling does not work

Ground Truth

Prediction:
Yield

Attack Modeling

Alpha Blending

Prediction:
Speed Limit (70 km/h)

Ray Tracing

Prediction:
Stop Sign

Naive trace modeling does not work

Attack Modeling

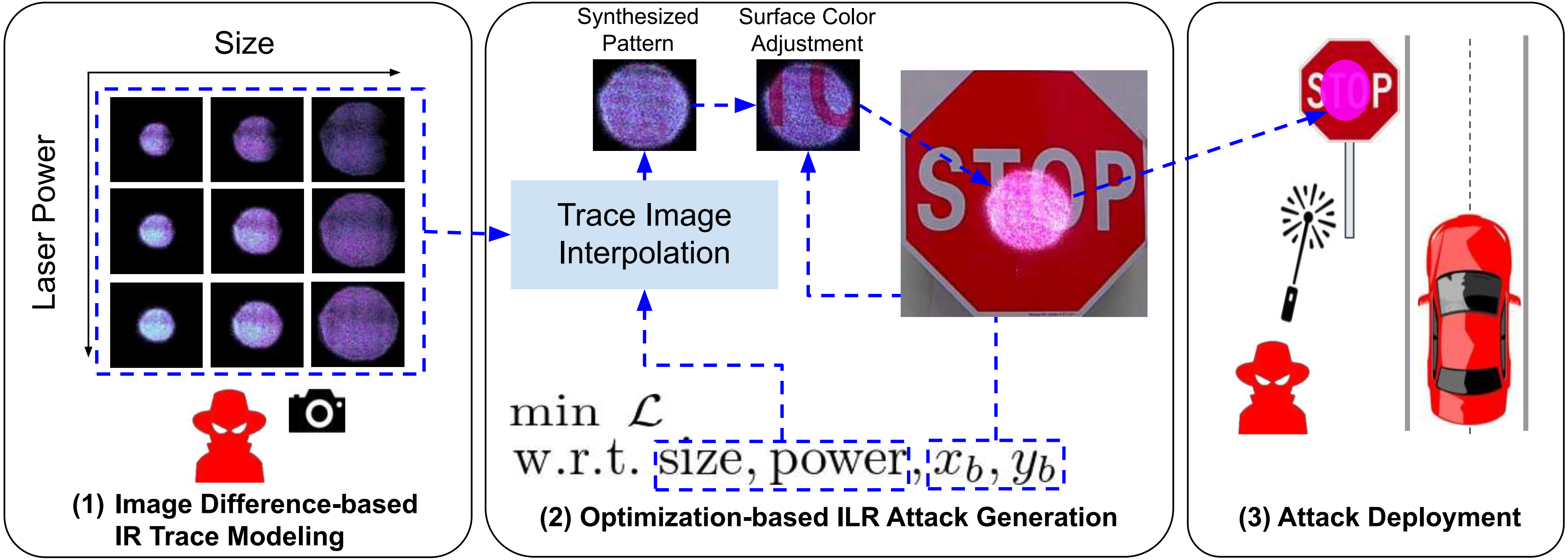
Ground Truth	**Alpha Blending**	**Ray Tracing**

Prediction:
Yield

Prediction:
Speed Limit (70 km/h)

Prediction:
Stop Sign

Overview of Attack Generation Pipeline



Our attack generation consists of 3 steps

Overview of Attack Generation Pipeline

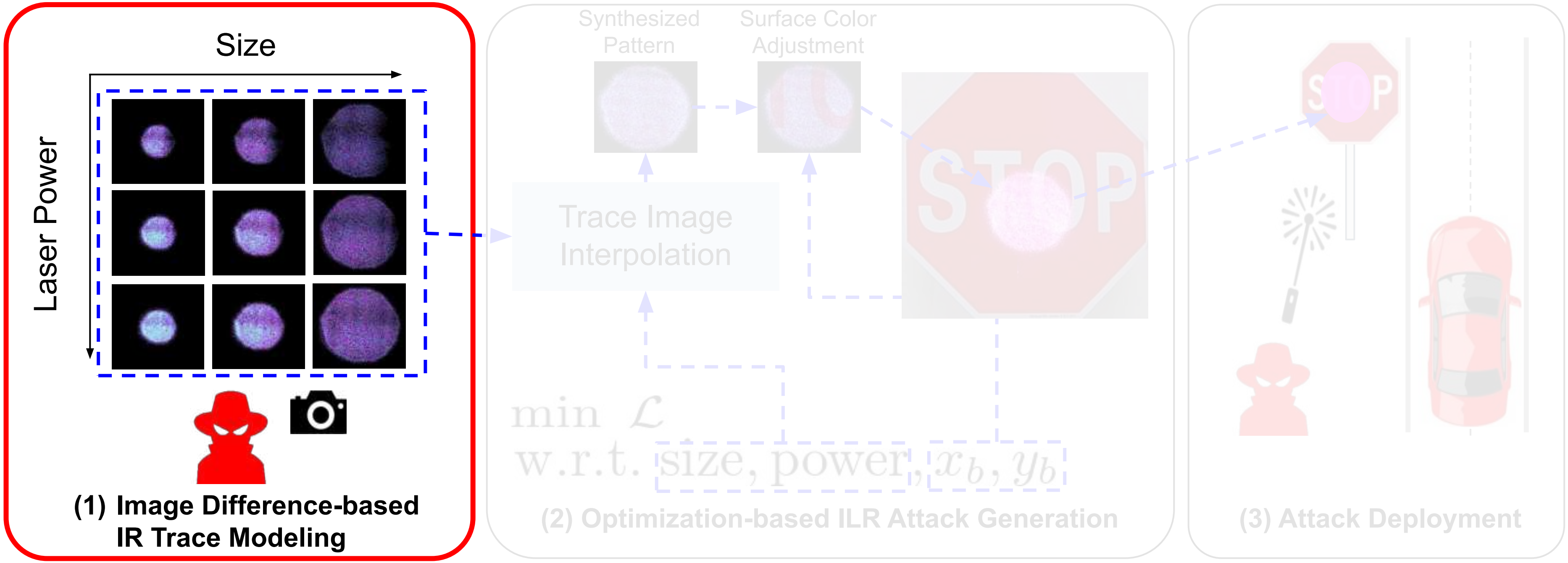
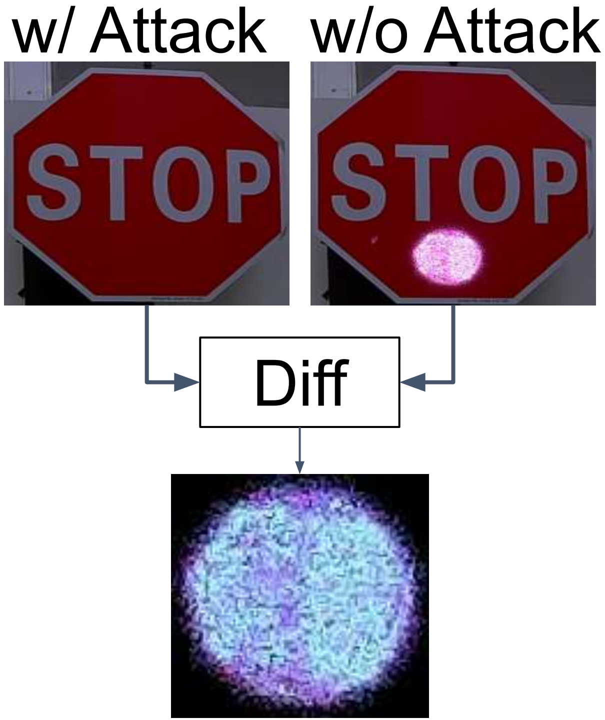


Image Difference-based IR Trace Modeling



Simple but no need to simulate complex speckle patterns

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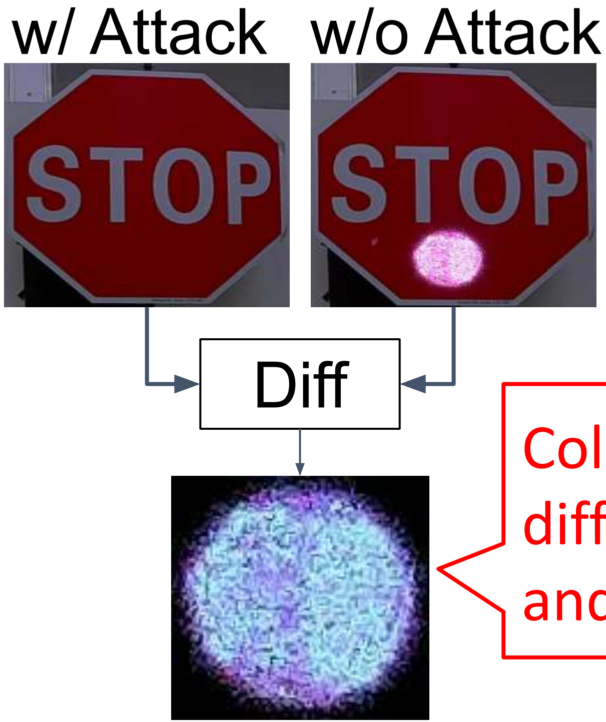

Collect trace diffs with different **laser powers** and **diameters.**

Simple but no need to simulate complex speckle patterns

Trace Image Interpolation

How to simulate *non-collected* traces?

- **Impossible to collect them physically**
- **Naive averaging dismisses the pattern**

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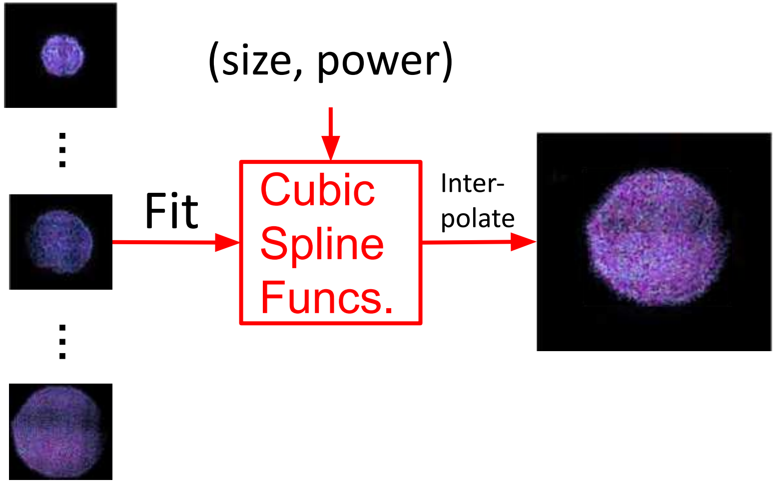
Pixel-wise Spline Interpolation

- Apply **cubic spline** for each pixel



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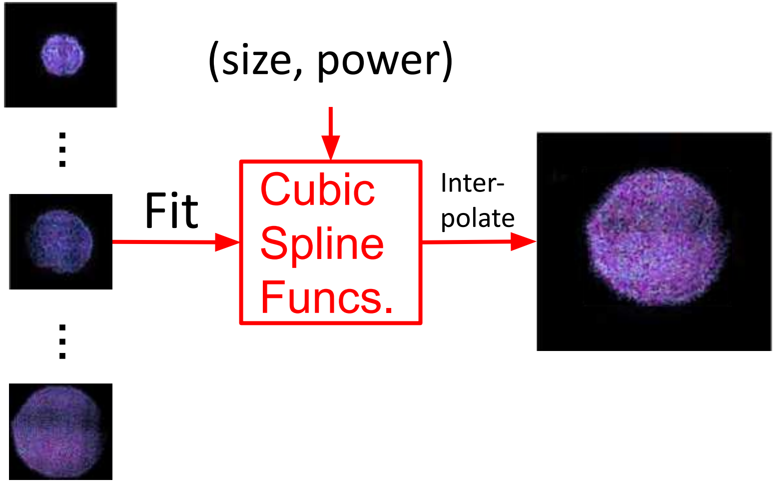
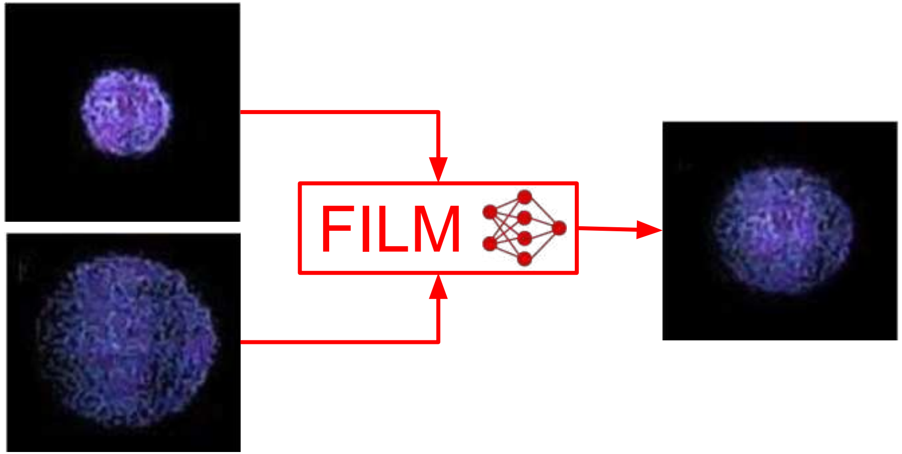


DNN-based Interpolation

- Apply **FILM** [Reda et al., 2022] model



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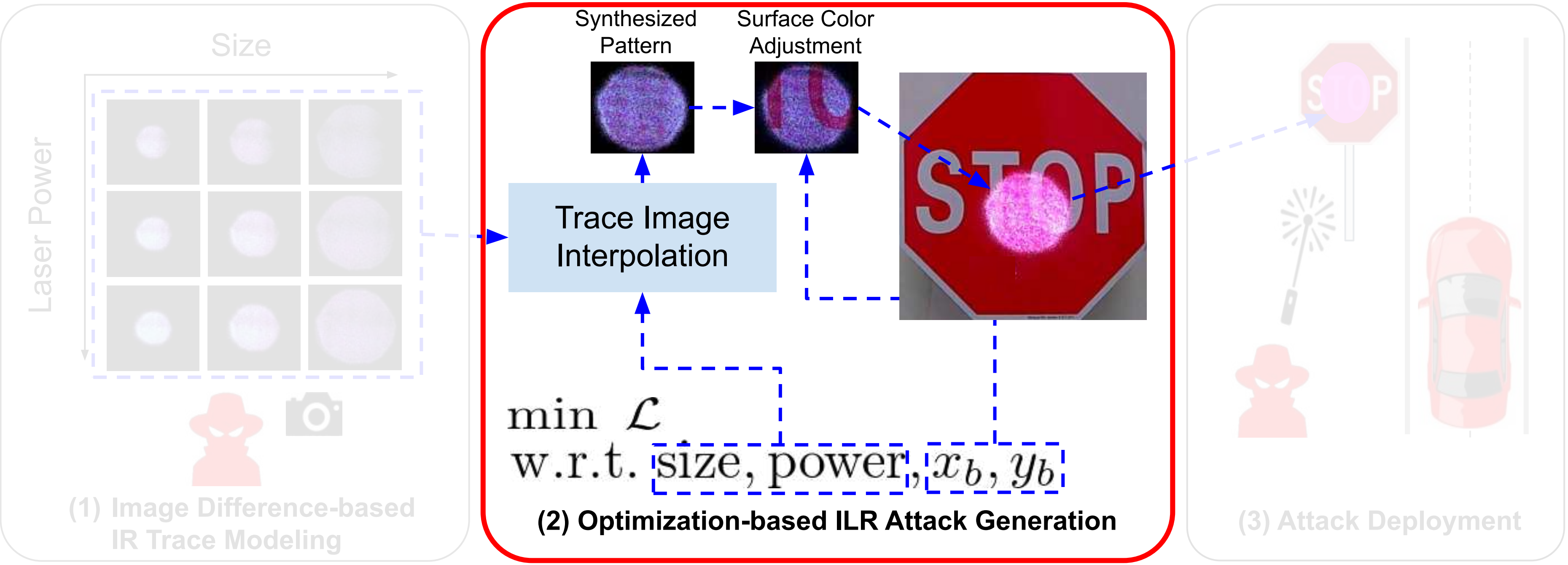
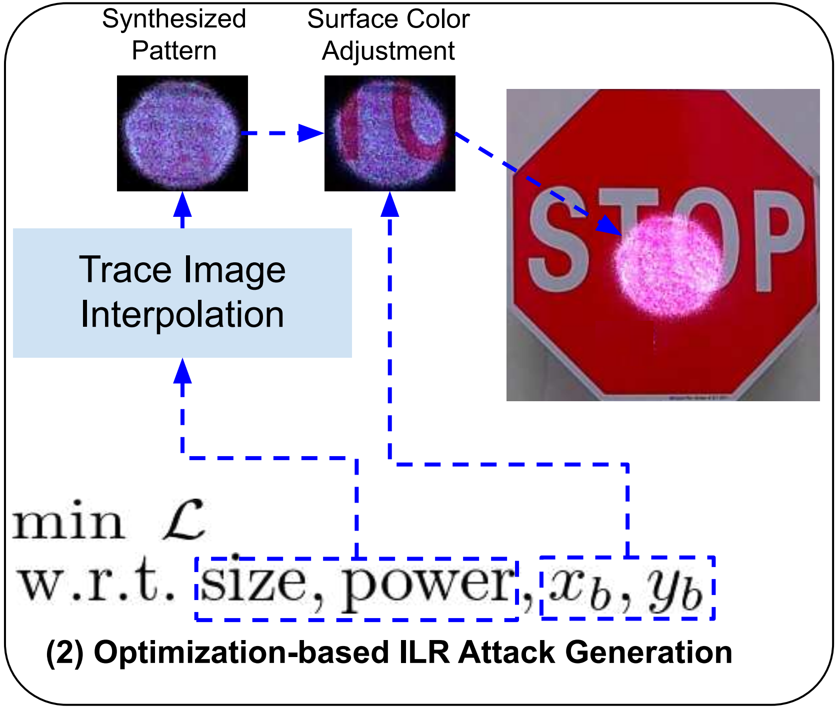


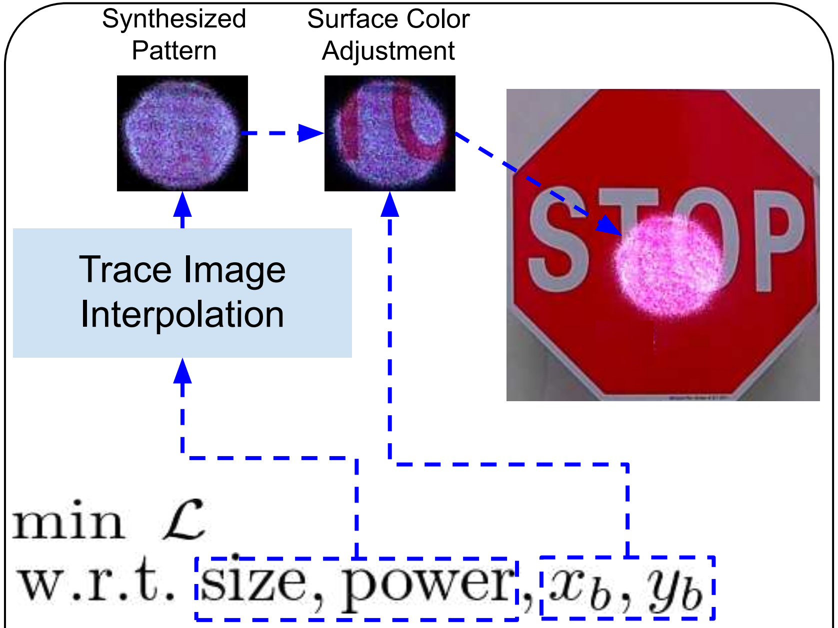
Optimization-based ILR Attack Generation



Black-box attack optimization

- Optimize attack trace w.r.t
  - size
  - power
  - position
- Use a bayesian optimization, Tree-Structured Parzen Estimator

Optimization-based ILR Attack Generation



(2) Optimization-based ILR Attack Generation

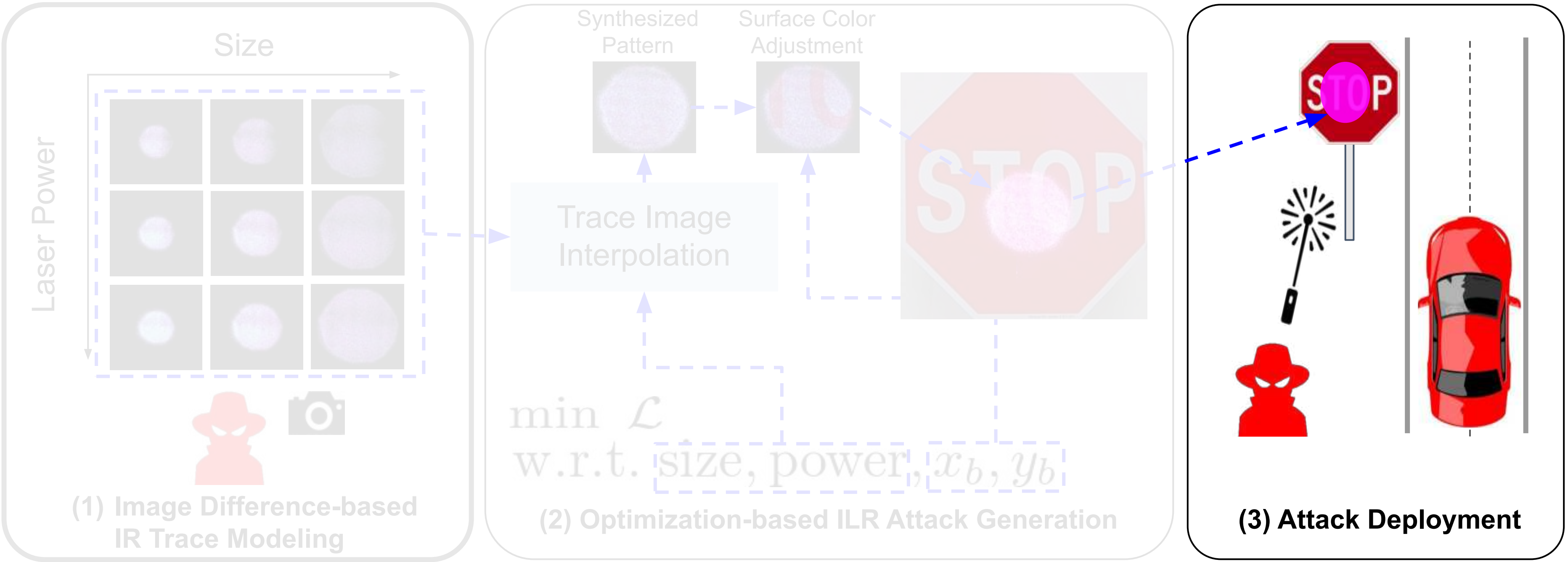
Black-box attack optimization

- Optimize attack trace w.r.t
  - size
  - power
  - position
- Use a bayesian optimization, Tree-Structured Parzen Estimator

Robustness improvement with Expectation over Transformation

- Resizing
- Brightness
- Gaussian Noise
- Rotation
- Shearing etc.

Overview of Attack Generation Pipeline



Attack Evaluation

** All attacks in this paper are physically deployed and evaluated*

Evaluation Criteria

- Effectiveness
- Generality
- Robustness
- Transferability

Evaluation Scenarios

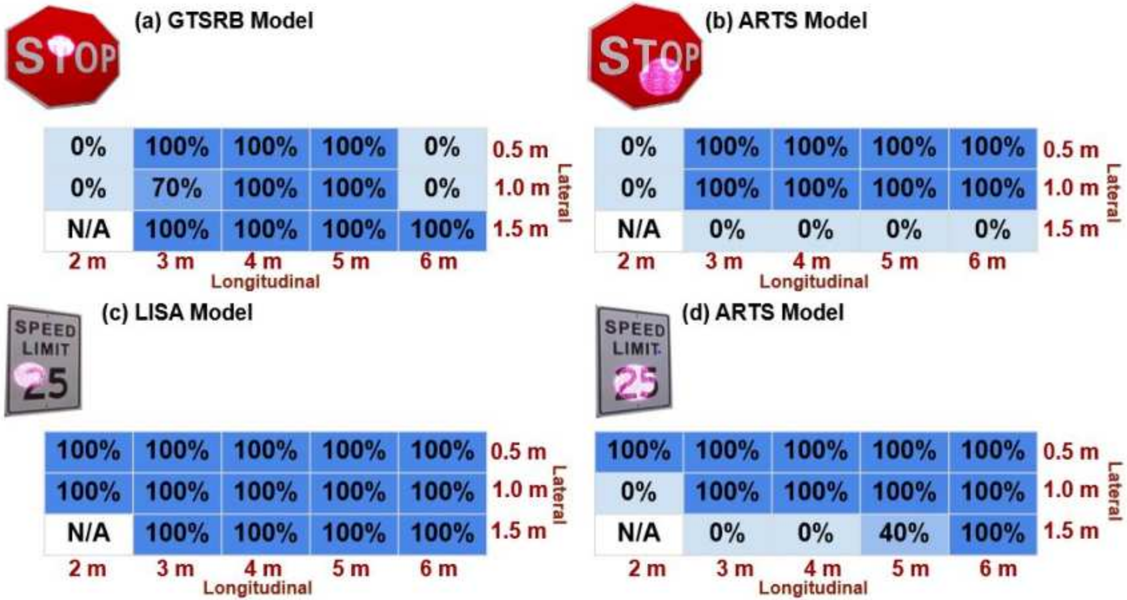
- Indoor
- Outdoor
    - Different lighting conditions
- Dynamic

Attack Factor Effectiveness

Target Traffic Sign Classification Models:
GTSRB, ARTS, LISA

Evaluation Factors:

- Lighting Conditions
- Victim Cameras
- Laser Modules
- Laser Orientations
- Camera Position



(a) GTSRB Model

Lateral \ Longitudinal	2 m	3 m	4 m	5 m	6 m
0.5 m	0%	100%	100%	100%	0%
1.0 m	0%	70%	100%	100%	0%
1.5 m	N/A	100%	100%	100%	100%

(b) ARTS Model

Lateral \ Longitudinal	2 m	3 m	4 m	5 m	6 m
0.5 m	0%	100%	100%	100%	100%
1.0 m	0%	100%	100%	100%	100%
1.5 m	N/A	0%	0%	0%	0%

(c) LISA Model

Lateral \ Longitudinal	2 m	3 m	4 m	5 m	6 m
0.5 m	100%	100%	100%	100%	100%
1.0 m	100%	100%	100%	100%	100%
1.5 m	N/A	100%	100%	100%	100%

(d) ARTS Model

Lateral \ Longitudinal	2 m	3 m	4 m	5 m	6 m
0.5 m	100%	100%	100%	100%	100%
1.0 m	0%	100%	100%	100%	100%
1.5 m	N/A	0%	0%	40%	100%

- Attack success rates reach **100%**, when camera is 3-5 m away from traffic sign
- Attack is more successful on speed limits - due to contrast with laser speckles

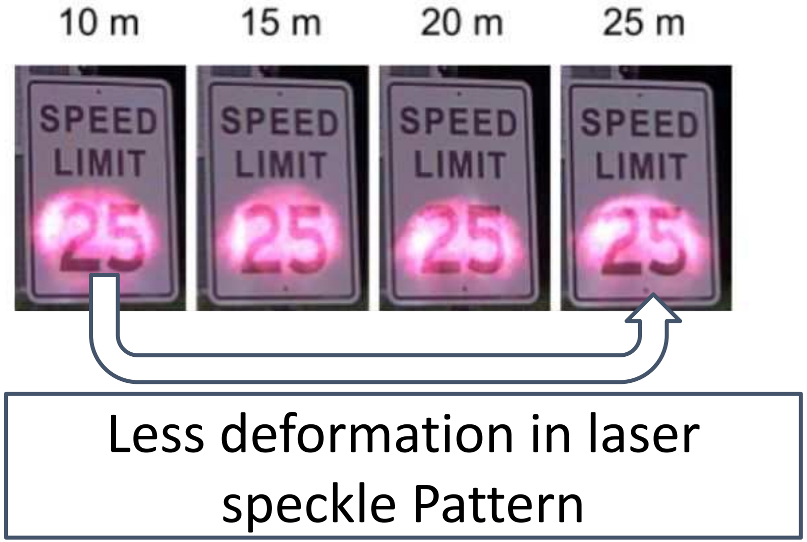
Attack on Object Detectors

- Attack success rates are **100%** at 6 m away from the target
  - YOLOv3 (single-stage object detector) shows higher robustness
- Attack is more robust on Speed Limit.

Target Sign	Detection Model	4 m	5 m	6 m	7 m
Stop Sign	Faster R-CNN (ARTS)	**100%**	**100%**	**100%**	**100%**
	YOLOv3 (COCO)	0%	0%	**100%**	0%
	YOLOv5 (COCO)	10%	90%	**100%**	**100%**
Speed Limit	Faster R-CNN (ARTS)	**100%**	**100%**	**100%**	**100%**
	Faster R-CNN (Mapillary)	**100%**	**100%**	**100%**	**100%**
	YOLOv5 (ARTS)	**100%**	**100%**	**100%**	**100%**

Maximum Attacker Distance

- Attack deployed from 25 meters with low power (26 mW).
- Long range attack due to laser properties
- Longer attack distances deform speckle, require sophisticated optics



Outdoor Attack Evaluation

	Stop Sign				Speed Limit			
	ARTS		GTSRB		ARTS		LISA	
Speed	ASR	SCR	ASR	SCR	ASR	SCR	ASR	SCR
Night Scenario								
5 km/h	**100%**	**100%**	99%	90%	**100%**	0%	99%	31%
8 km/h	**100%**	**100%**	92%	91%	**100%**	0%	**100%**	0%
13 km/h	**100%**	**100%**	85%	85%	**100%**	0%	99%	16%
Day Scenario								
5 km/h	98%	82%	85%	57%	**100%**	18%	**100%**	98%
8 km/h	**100%**	88%	88%	46%	**100%**	50%	**100%**	87%
13 km/h	91%	75%	80%	40%	**100%**	58%	**100%**	98%

Outdoor Attack Evaluation

	Stop Sign				Speed Limit			
	ARTS		GTSRB		ARTS		LISA	
Speed	ASR	SCR	ASR	SCR	ASR	SCR	ASR	SCR
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5 km/h	**100%**	**100%**	99%	90%	**100%**	0%	99%	31%
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13 km/h	**100%**	**100%**	85%	85%	**100%**	0%	99%	16%
Day Scenario								
5 km/h	98%	82%	85%	57%	**100%**	18%	**100%**	98%
8 km/h	**100%**	88%	88%	46%	**100%**	50%	**100%**	87%
13 km/h	91%	75%	80%	40%	**100%**	58%	**100%**	98%

- High attack success rates for 2 models trained on popular datasets
  - 🌙 Night time (120 lux) : **≧85%** attack success rate
  - 🌞 Day time (982 lux) : **≧80%** attack success rate

Limitation of State-of-Art Certifiable Defense

- **PatchCleanser** [Xiang et al., 2022] **does not handle ILR attack well**
  - Assume prediction holds without adversarial trace
  - Their intuition doesn’t hold, i.e., small part making can change label
- PatchCleanser’s key idea, 2-round masking, can cause false agreements
- Mis-certifies ≥33.5% of cases of ILR attack traces

Proposed Defenses

Color-Frequency Detection: Physics-based characteristics of laser light reflections

Speckle Color Range based on ambient illumination

- #CF9FFF and #DA70D6 (Low illumination)
- #FFB266 to #CC6600 (High illumination)

Traffic Sign with ILT attack trace | Speckle Color Range | High Spatial Frequency

Evaluated on 300 images during daytime and nighttime scenarios

- 98% True Positive Rate and 2.7% False Positive Rate during daytime conditions
- 92% True Positive Rate and 6.7% False Positive Rate during nighttime conditions

Conclusion

Discovered ILR, **a long-distance and human-invisible attack vector,** that can cause misclassification by **traffic sign recognition systems**.

- **Design a novel methodology to optimize attack**
  - Image difference-based IR trace modeling
  - Trace image interpolation
  - Robust attack generation with black-box optimization
- **Measure the characteristics of ILR with a wide variety of parameters**
- **Perform evaluation in both indoor and outdoor day/night setups**
  - **100%** attack success rate indoor setup
  - **≥80.5%** attack success rate in outdoor driving setup up to 13 Km/h at day and night
- **Demonstrate the limitations in the current state-of-the-art defense**
- **Design a new defense leveraging characteristics of ILR**

Thank you!

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