Eliminating Inter-Domain Vulnerabilities in Cyber-Physical Systems: **An Analysis Contracts Approach**

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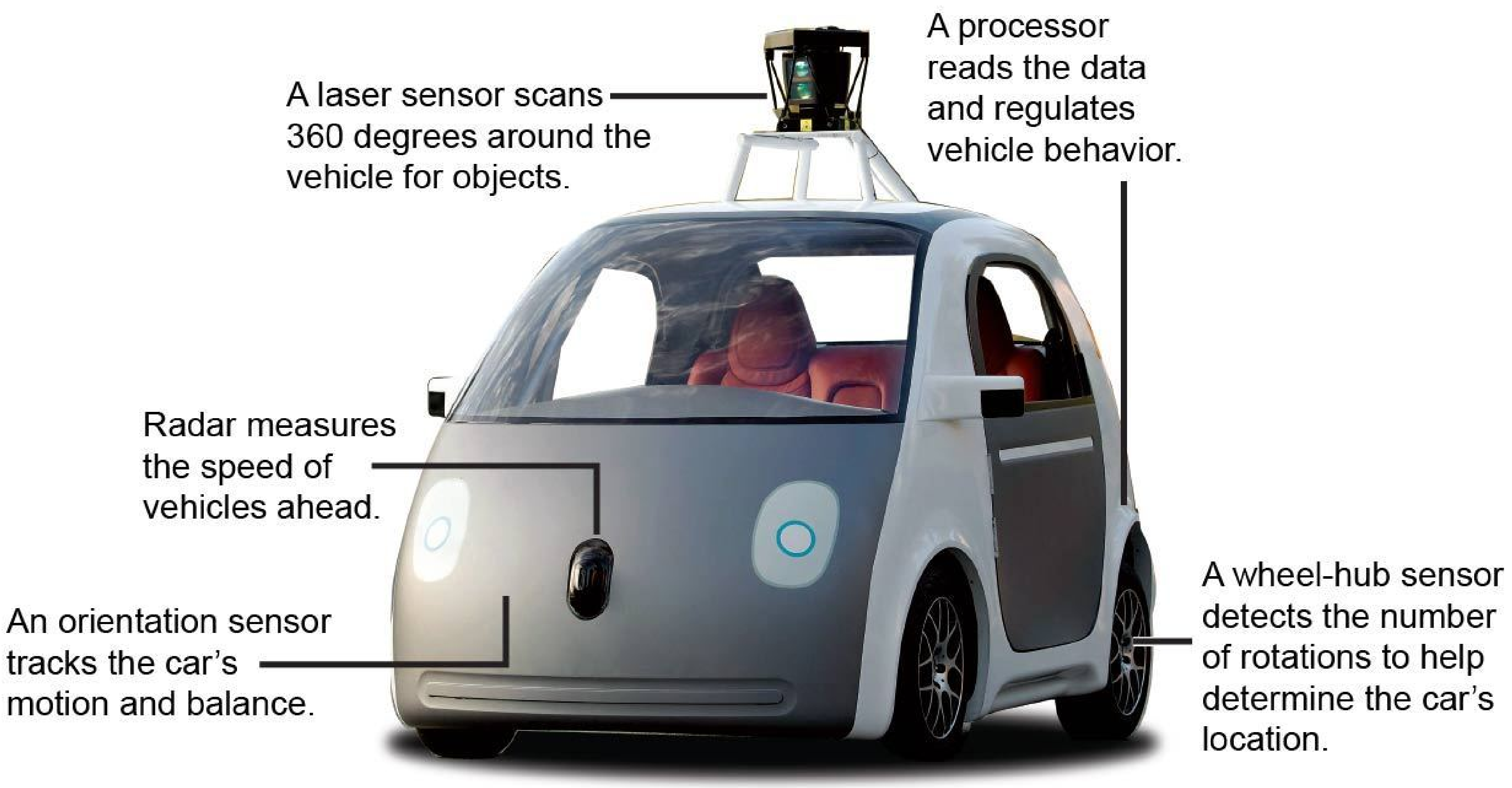
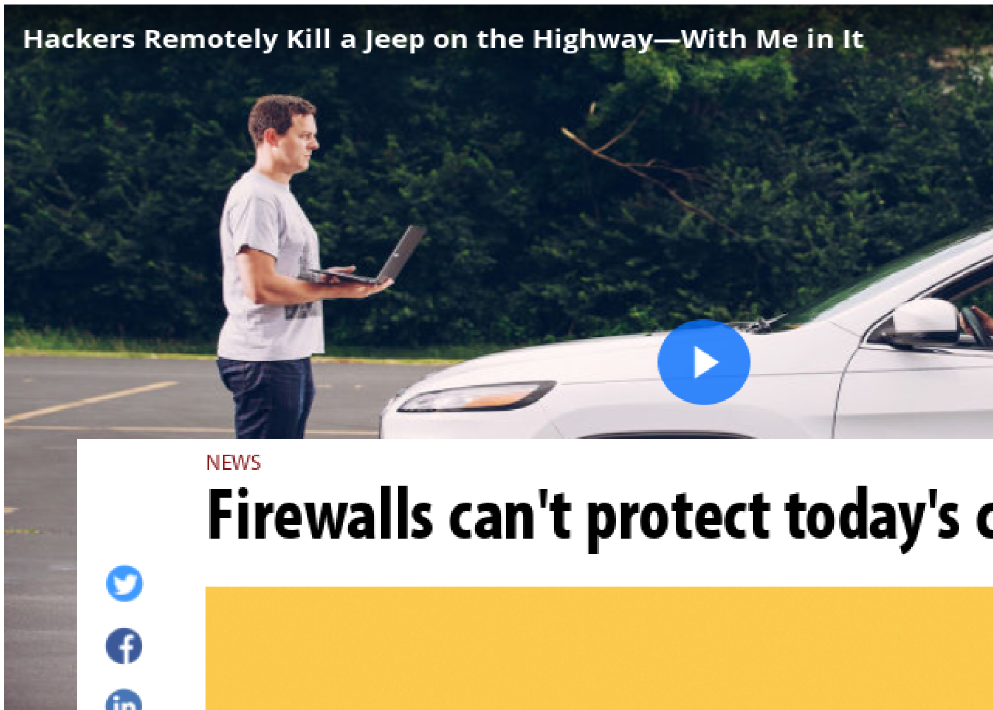


- Safety, efficiency, fault-tolerance
  - Formal verification, control theory, reliability engineering, ...

HACKERS REMOTELY KILL A JEEP ON THE HIGHWAY—WITH ME IN IT



Researcher Hacks Self-driving Car Sensors

By Mark Harris
Posted 4 Sep 2015 | 19:00 GMT

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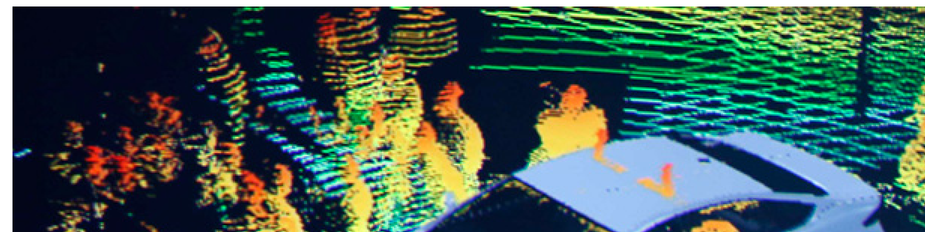

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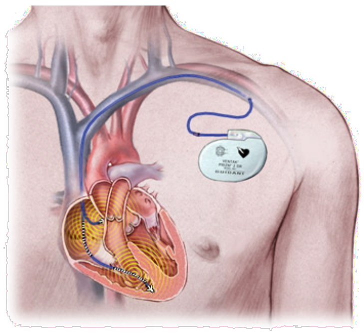
Cyber-Physical Systems and Vulnerabilities

- Software-controlled distributed autonomy
- Complex physical behavior



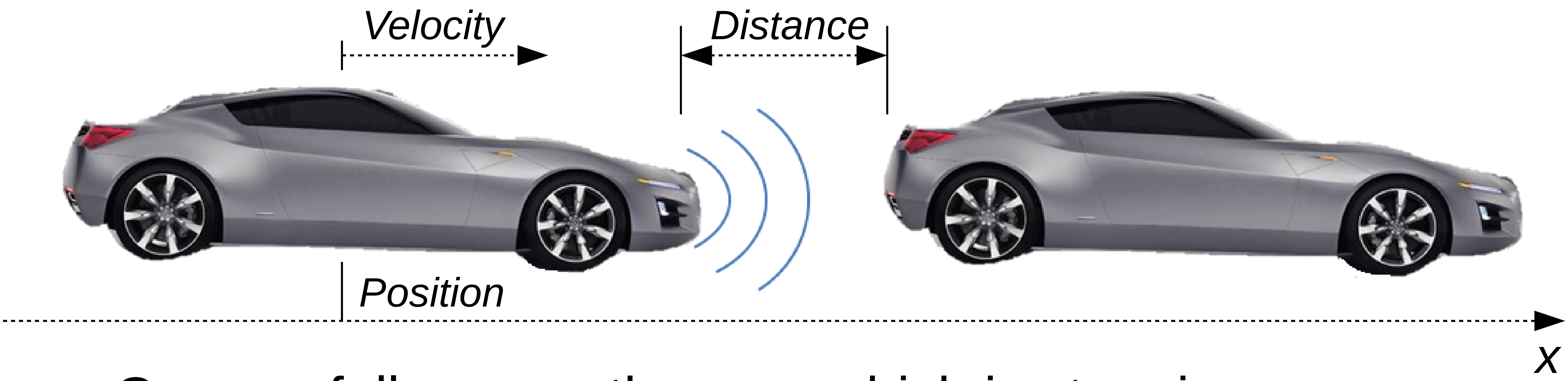



- Diverse interactions: networks, physics, …
  - Potentially malicious
- Diverse attack surfaces and vulnerabilities

Outline

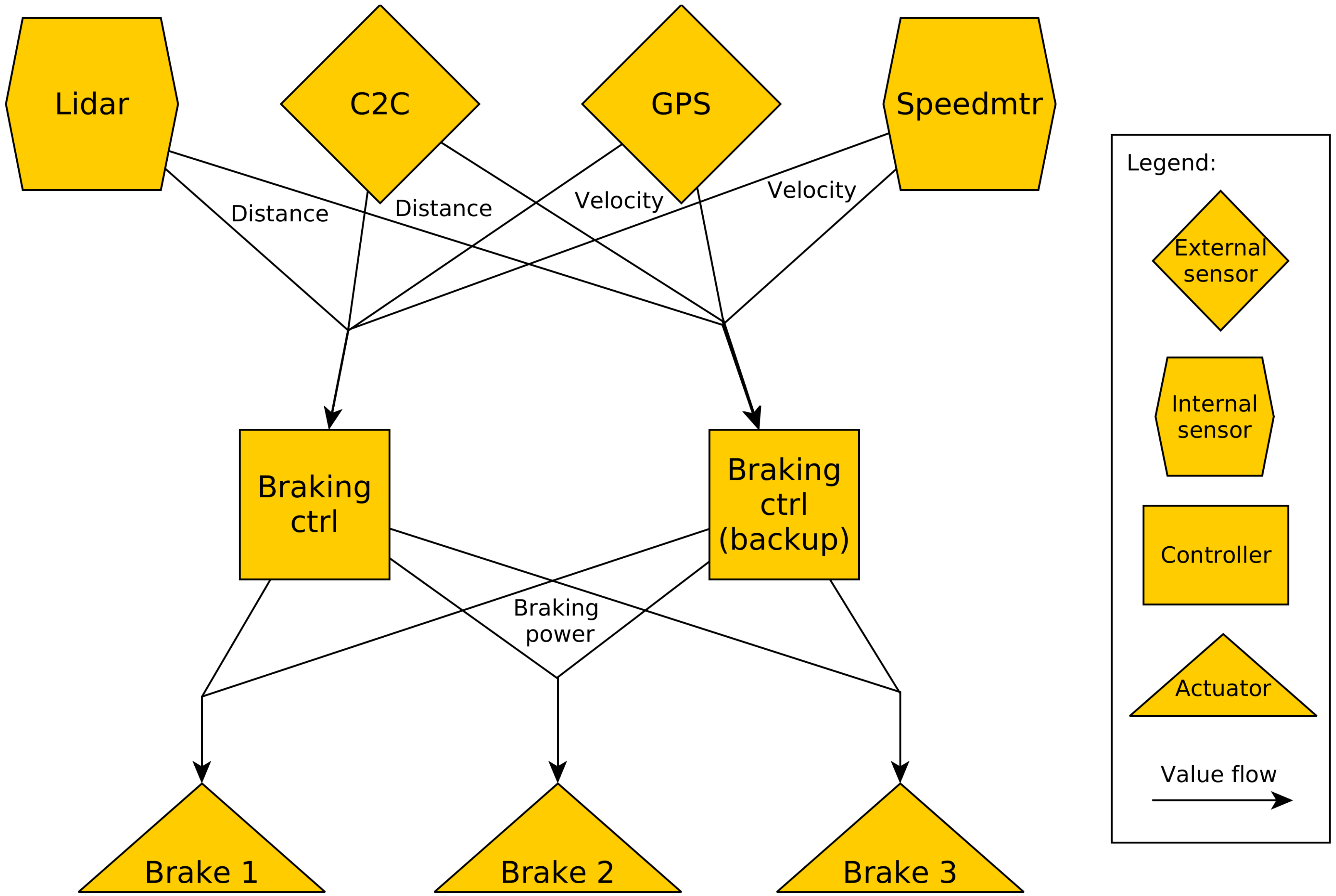
- Security in cyber-physical systems
- **Inter-domain vulnerabilities**
- Analysis contracts approach
- Discussion

Scenario



- One car follows another car, which is stopping.
- Senses position, distance, and velocity.
- *Safety:* must brake and stop without crashing.
  - Depends on effective *control:* slows down smoothly (esp. on ice)
  - Depends on *reliability:* stops even if a sensor malfunctions
  - Depends on *sensor security:* stops even if a sensor is spoofed

Braking Subsystem Architecture



Full model: *github.com/bisc/collision_detection_aadl*

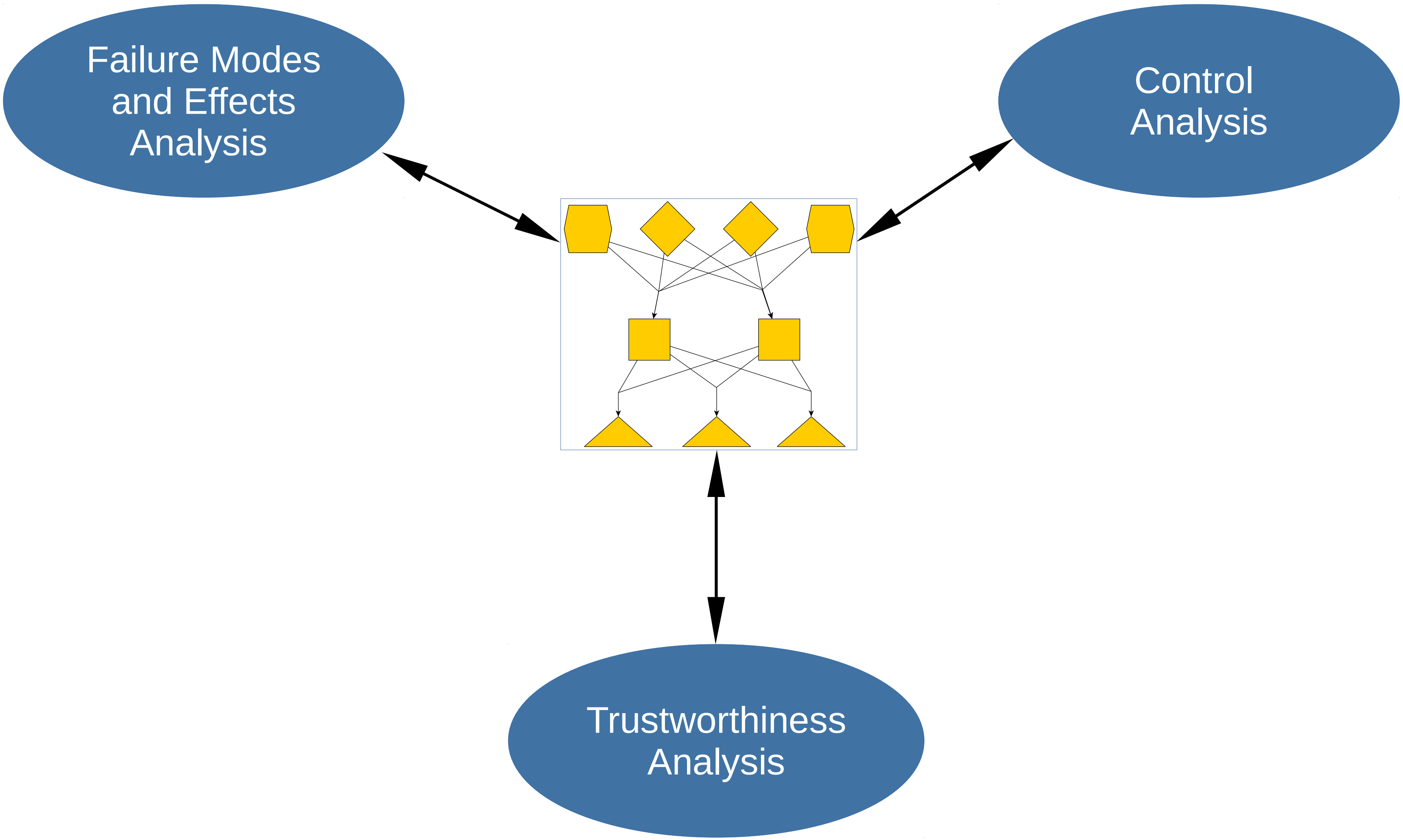
Exploiting Sensors

- Adversary models:
  - Knows the system's architecture
  - Internal or external (not all-powerful)
  - Spoofs data for respective sensor type
- Attack steps (online):

  1. Find a vulnerable set of sensors in a car
  2. Spoof all of the sensors in the set

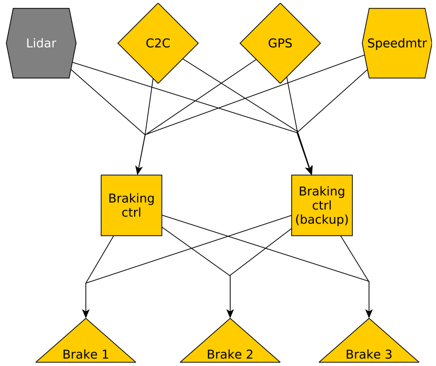
  Impact: the control is misled and possibly crashes

Analyses (offline)

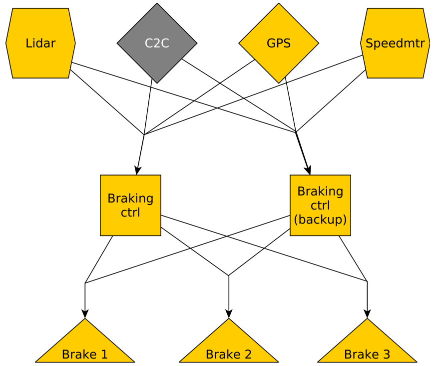


Analysis 1: FMEA

- *Failure Modes and Effects Analysis* [Schneider1996]
  - Mature and common in reliability engineering
- Goals:
  1. Determine most likely “failure modes”
     - Configurations where some components failed



P = 0.1



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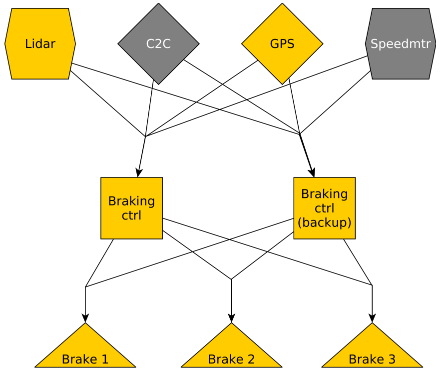


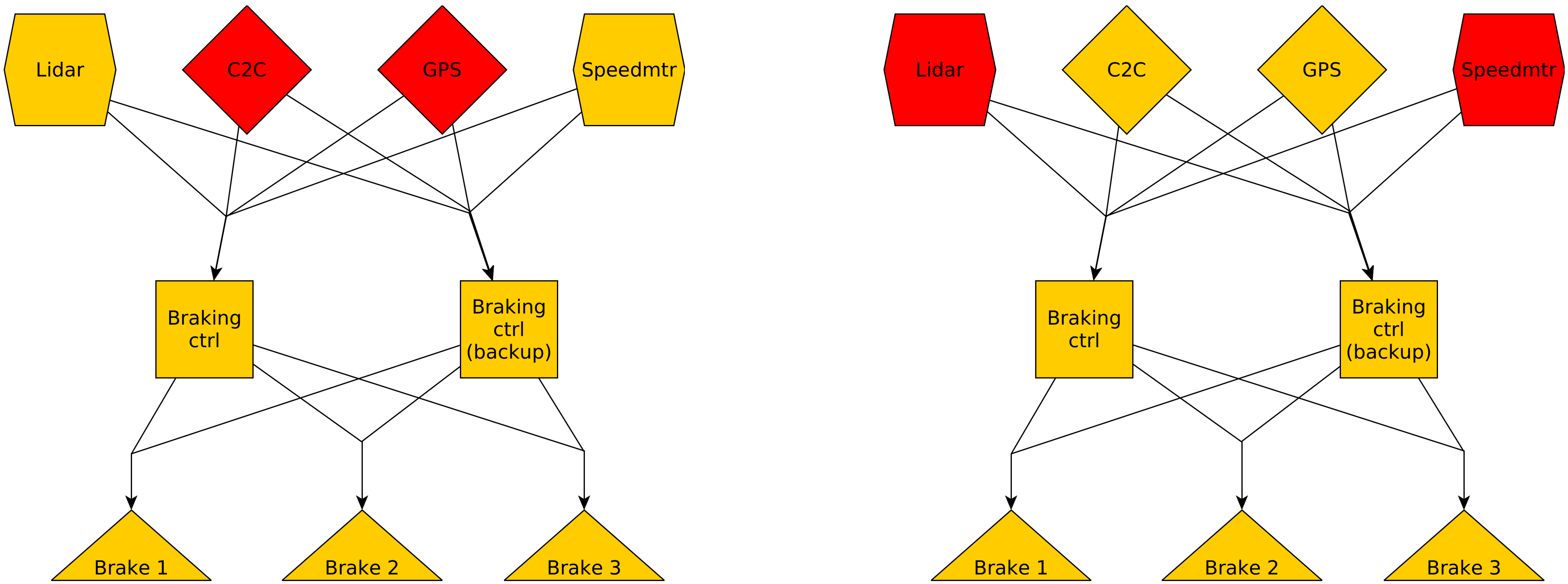
P = 0.01

  2. Augment the system to reduce failure likelihood

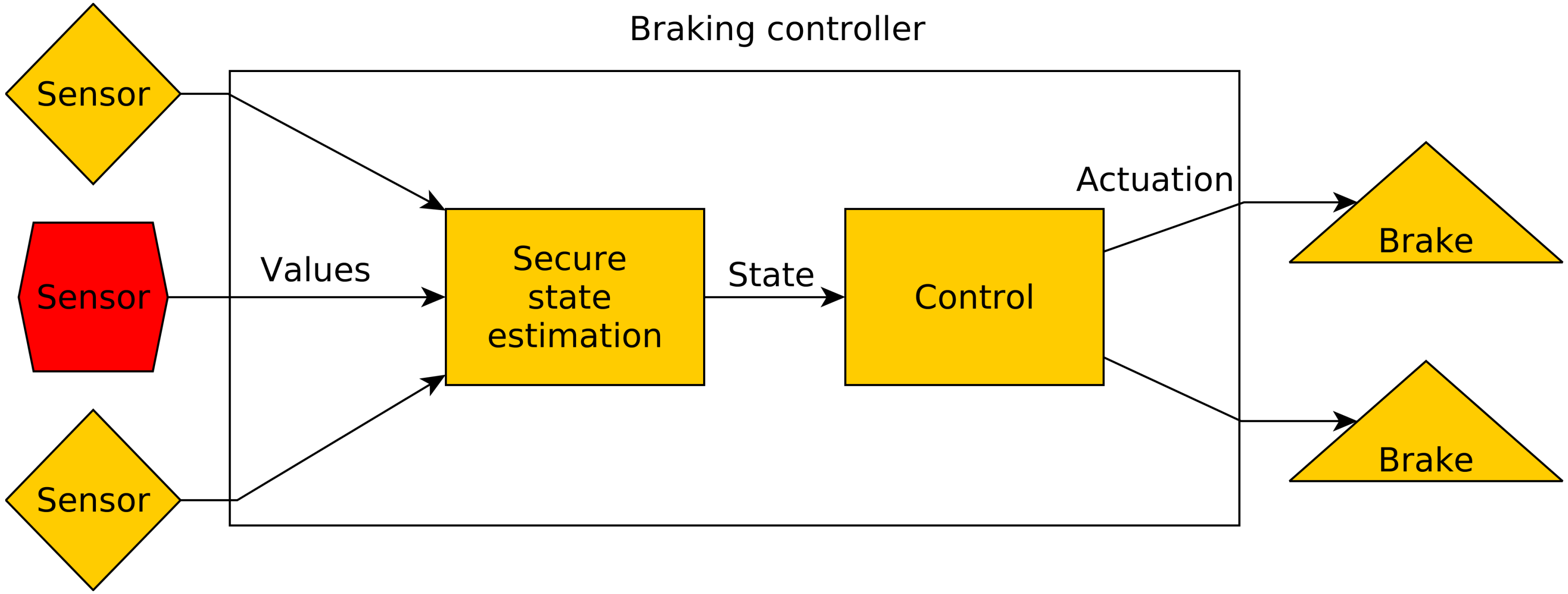
Analysis 2: Sensor Trustworthiness

- Goal: determine trustworthiness of each sensor
  - Given an attacker model [Miao2013]

Internal attacker *External attacker*



Analysis 3: Secure Control



- Goals: [Fawzi2014]

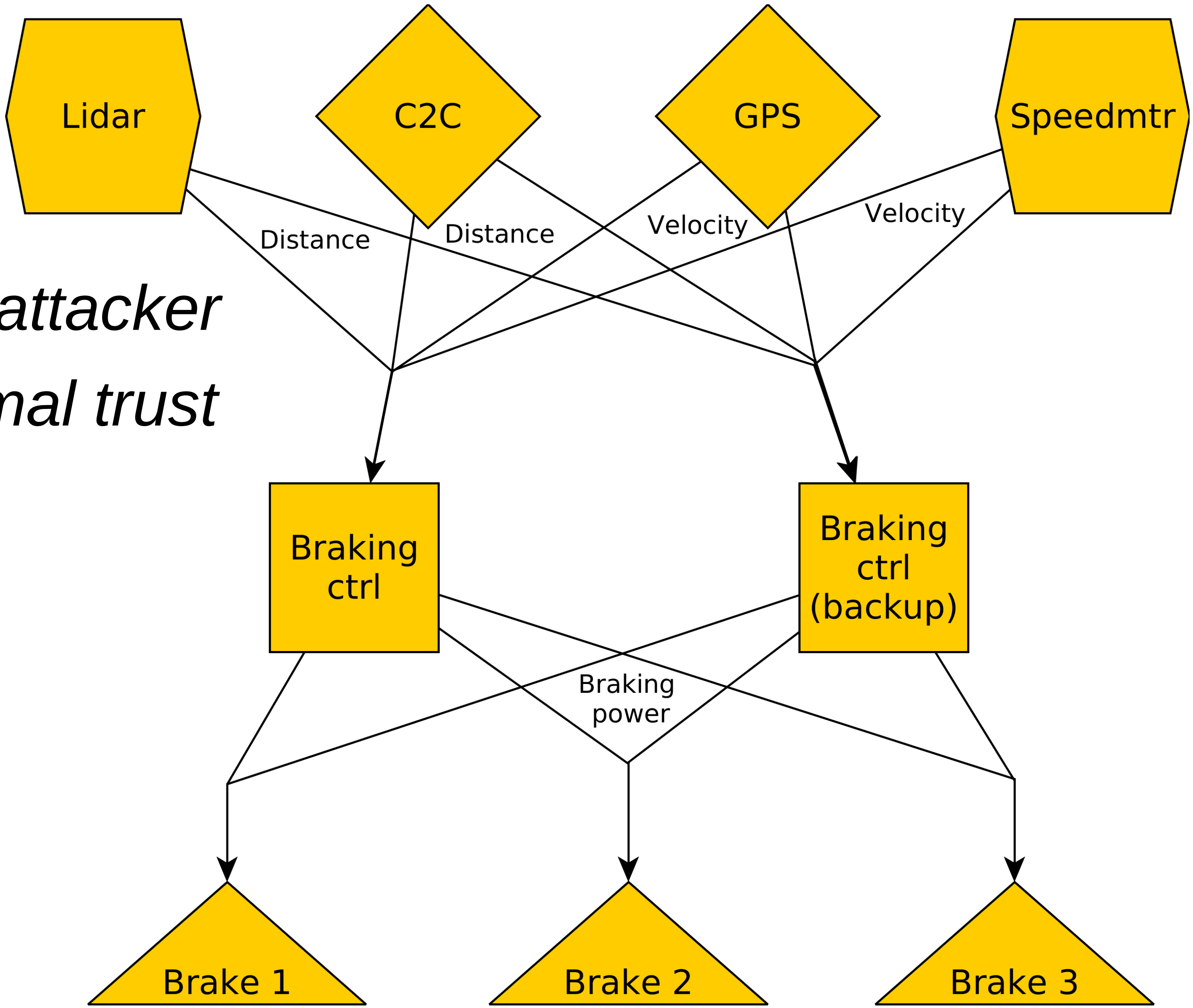
1. Tune controllers and state estimators
2. Determine if control is safe and smooth

- **Minimal sensor trust assumption:** at least 50% sensors are providing trustworthy data (for each sensed variable)

Exploiting Vulnerability

Internal attacker

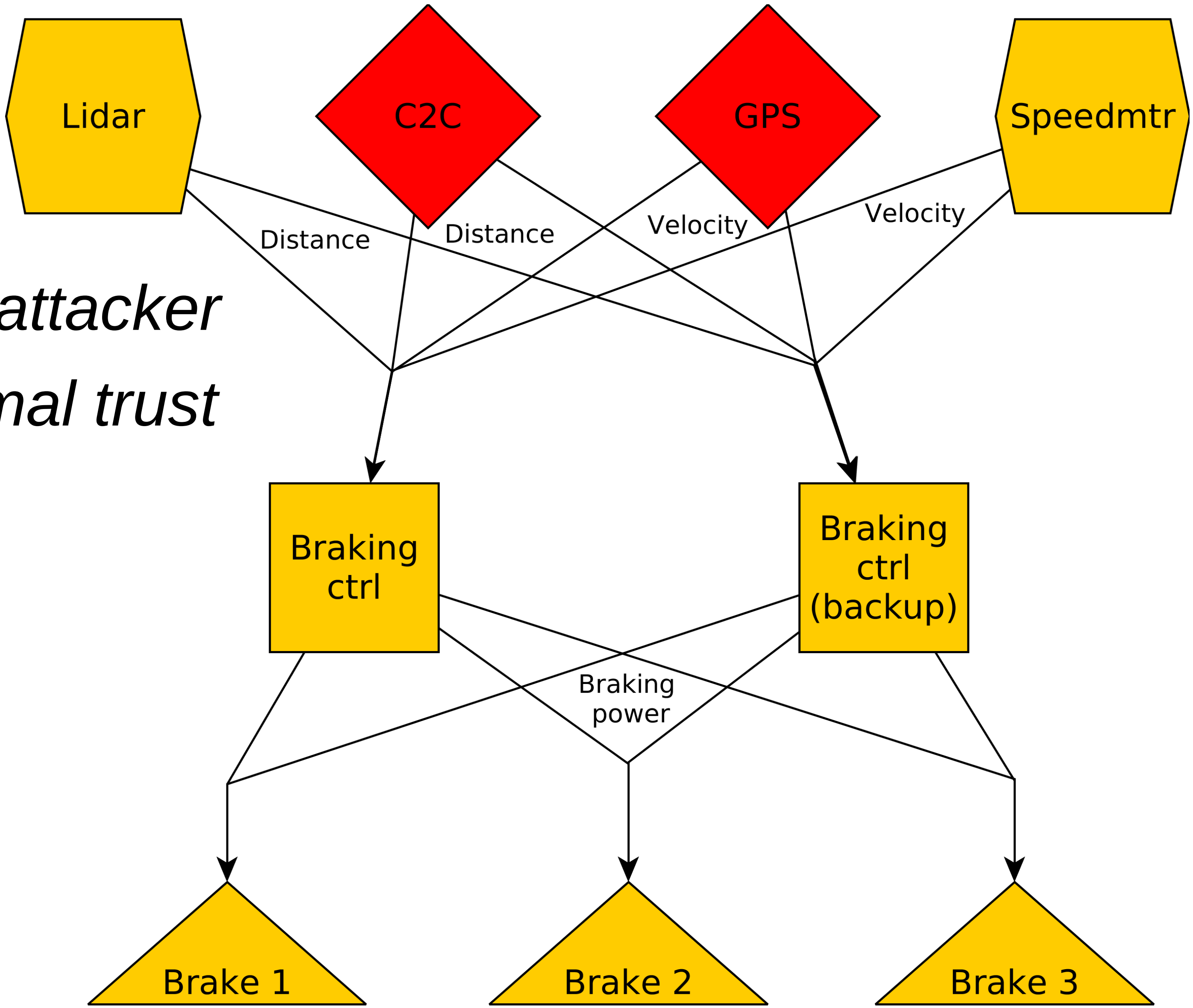
✔ *minimal trust*



Exploiting Vulnerability

Internal attacker

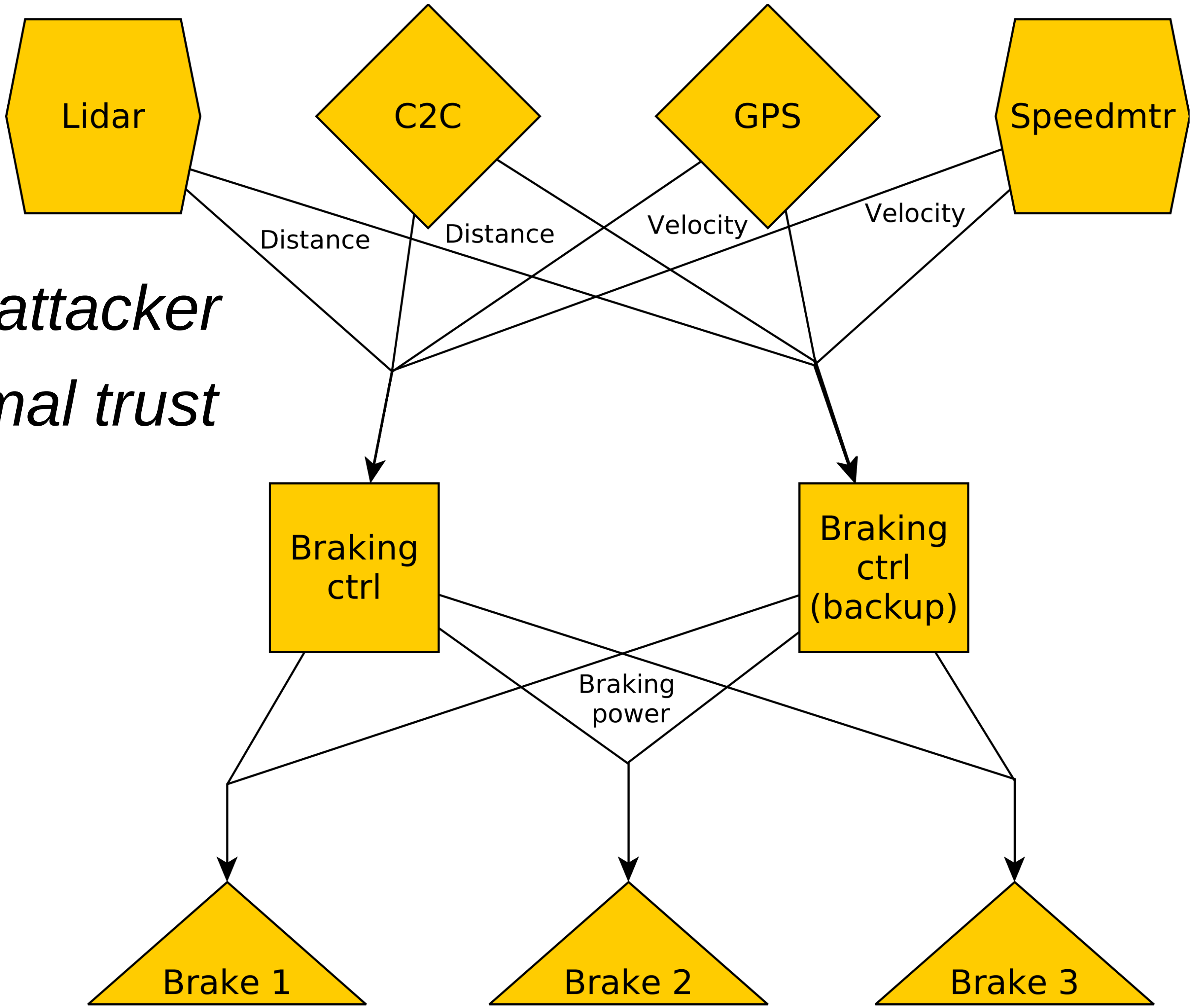
✓ *minimal trust*



Exploiting Vulnerability

Internal attacker

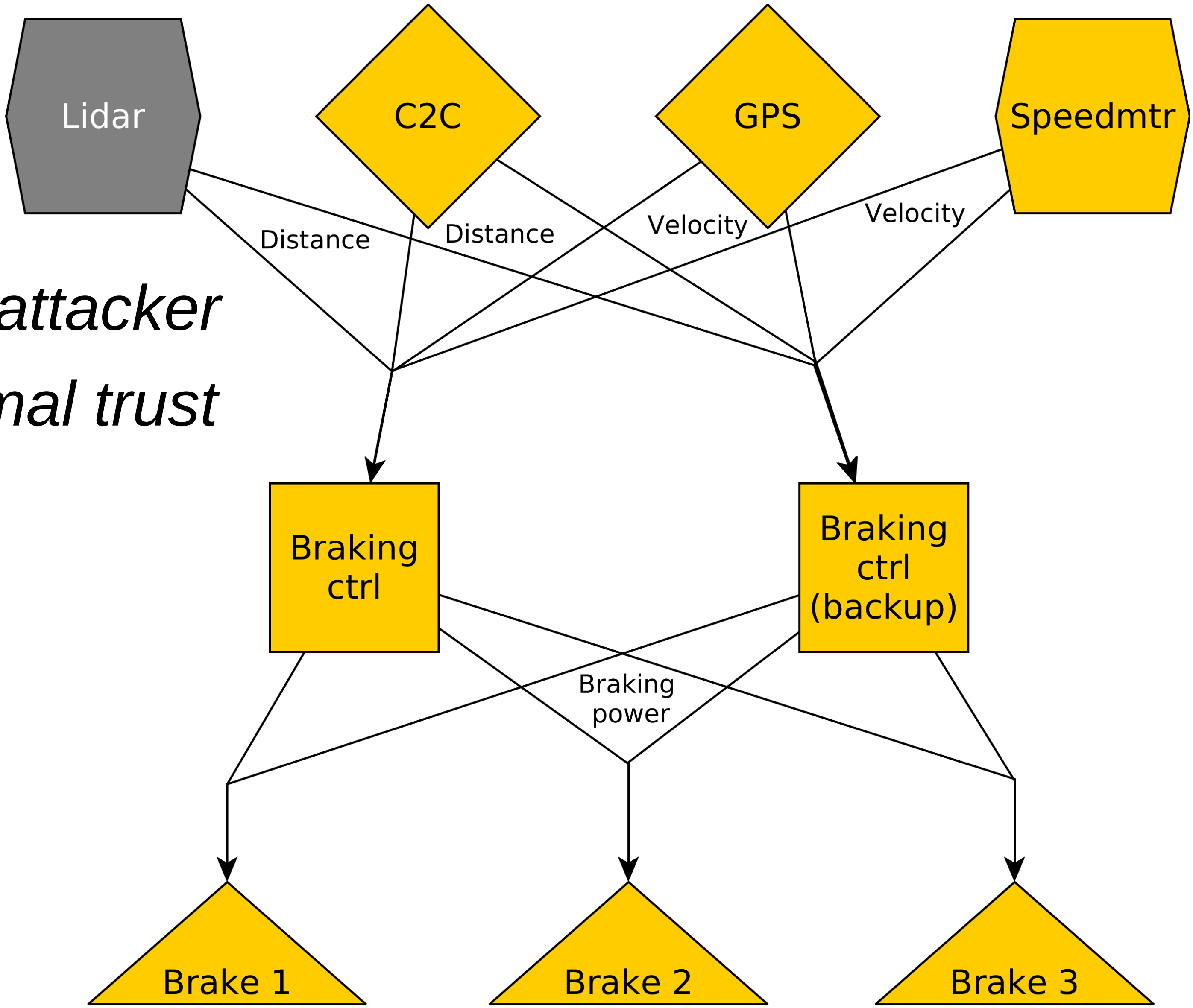
✔ *minimal trust*



Exploiting Vulnerability

Internal attacker

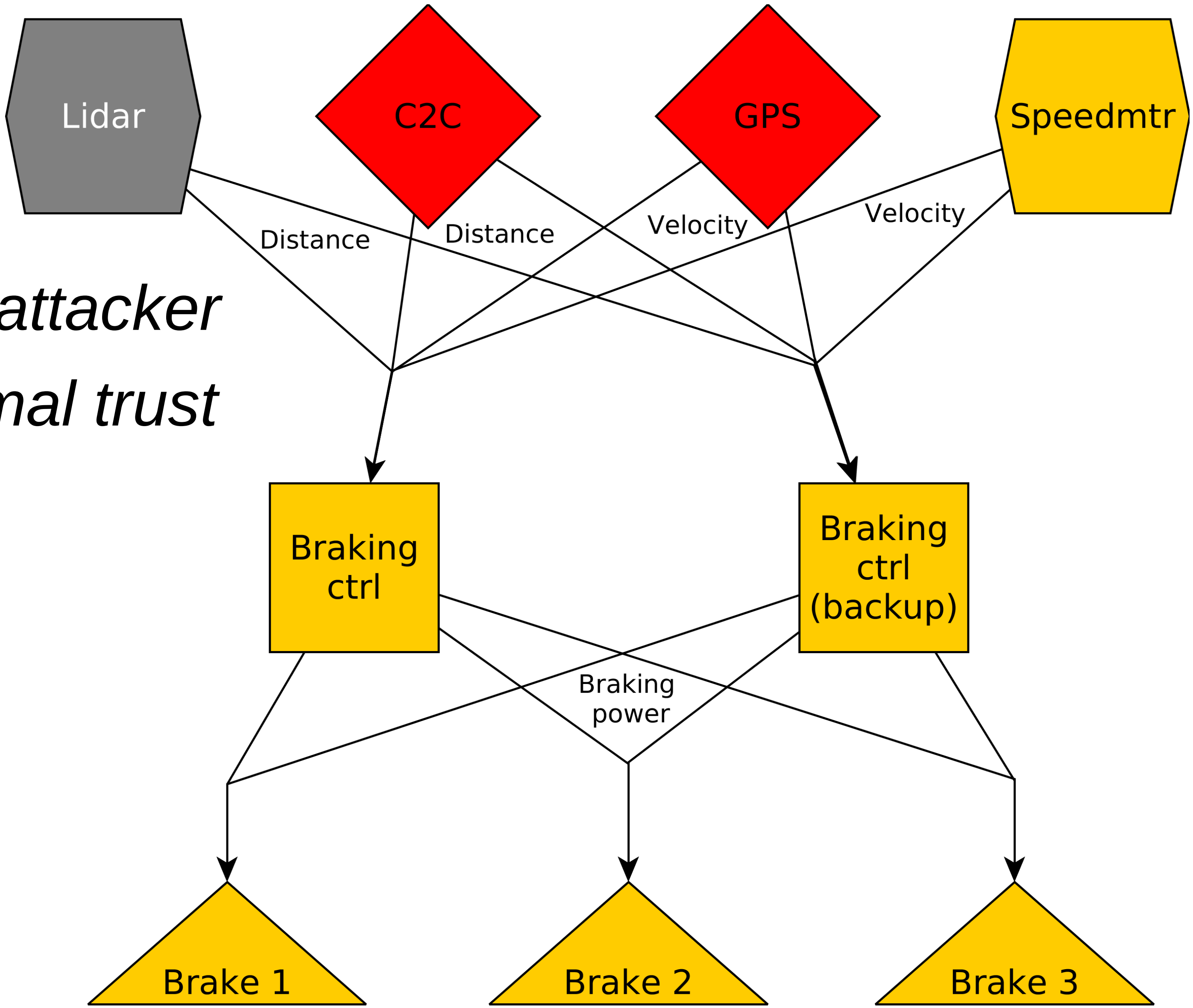
✔ *minimal trust*



Exploiting Vulnerability

Internal attacker

✖ *minimal trust*



Problem: Inter-Domain Vulnerabilities

- Uncontrolled *analysis interactions* may lead to introduction of vulnerabilities into CPS.
- *Cause:* unsatisfied dependencies and assumptions.
- Introduced offline, exploited online.

Outline

- Security in cyber-physical systems
- Inter-domain vulnerabilities
- **Analysis contracts approach**
- Discussion

Possible Solutions

- Cybersecurity **online**: IDS, firewalls
  - Oblivious of diverse engineering analyses
- Cybersecurity **offline**: encryption, secure protocols, secure-by-design
  - May not work with physical world
- **Control-theoretic** CPS security *[Fawzi2014]*
  - Does not consider fault-tolerance and other factors
- **Component** modeling, interface theories
  - Focuses on system parts, not quality concerns

Analysis Contracts Approach

1. Model the system's architecture
2. Formalize *contracts* for analyses *[Ruchkin2014]*
   - Inputs, outputs, assumptions, guarantees
3. Execute analyses correctly (offline)
   - Dependencies met
   - Assumptions satisfied

- *Expectation:* inter-domain vulnerabilities are detected and prevented

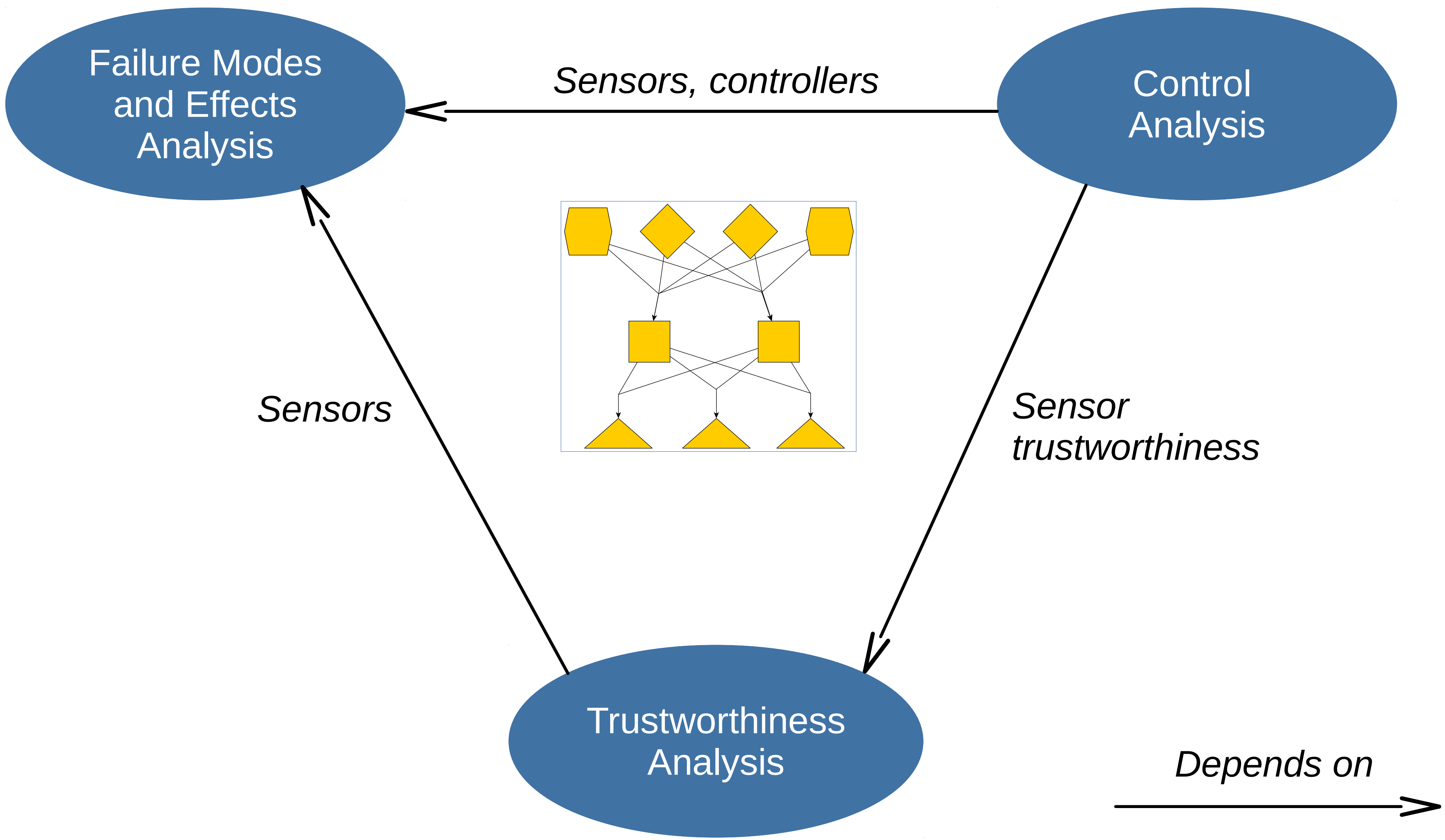
Step 1: Architecture Modeling

- AADL – *Architecture Analysis and Design Language* [Feiler2005]
- Provides standardized high-level vocabulary
  - *Components and connectors:* sensors, controllers, actuators, …
  - *Properties:* sensor variables, trustworthiness, attacker model, ...
  - *Modes:* configurations of components, connectors, and their properties

Step 2: Analysis Contract Specification

Analysis	Input	Output
FMEA	Fault-tolerance requirements	**Sensors**, **controllers**, modes
Trustworthiness	**Sensors**, attacker model	Sensor trustworthiness
Control	**Sensors**, **controllers**	Control safety

Analytic Dependencies



Assumptions and Guarantees

- Logically specify for each analysis
- Ctrl analysis assumption (minimal sensor trust):

$$\forall m \in \mathbb{M} \cdot |m.S_{trustworthy}| / |m.\mathbb{S}| \geq 0.5$$

- Actual second-order encoding in SMTv2:

$$\begin{aligned} &\forall m \in \mathbb{M}\ \forall c \in m.\mathbb{R}, v \in c.\mathsf{VarsR} \cdot \\ &\quad \exists f : \mathbb{S} \to \mathbb{S} \cdot \forall s_u \in m.\mathbb{S} \cdot \\ &\qquad v \in s_u.\mathsf{VarsS} \wedge s_u.\mathsf{Trust} = \bot \implies \\ &\qquad \exists s_t \in m.\mathbb{S} \cdot v \in s_t.\mathsf{VarsS} \wedge s_t.\mathsf{Trust} = \top \wedge f(s_t) = s_u \end{aligned}$$

Step 3: Contract Verification

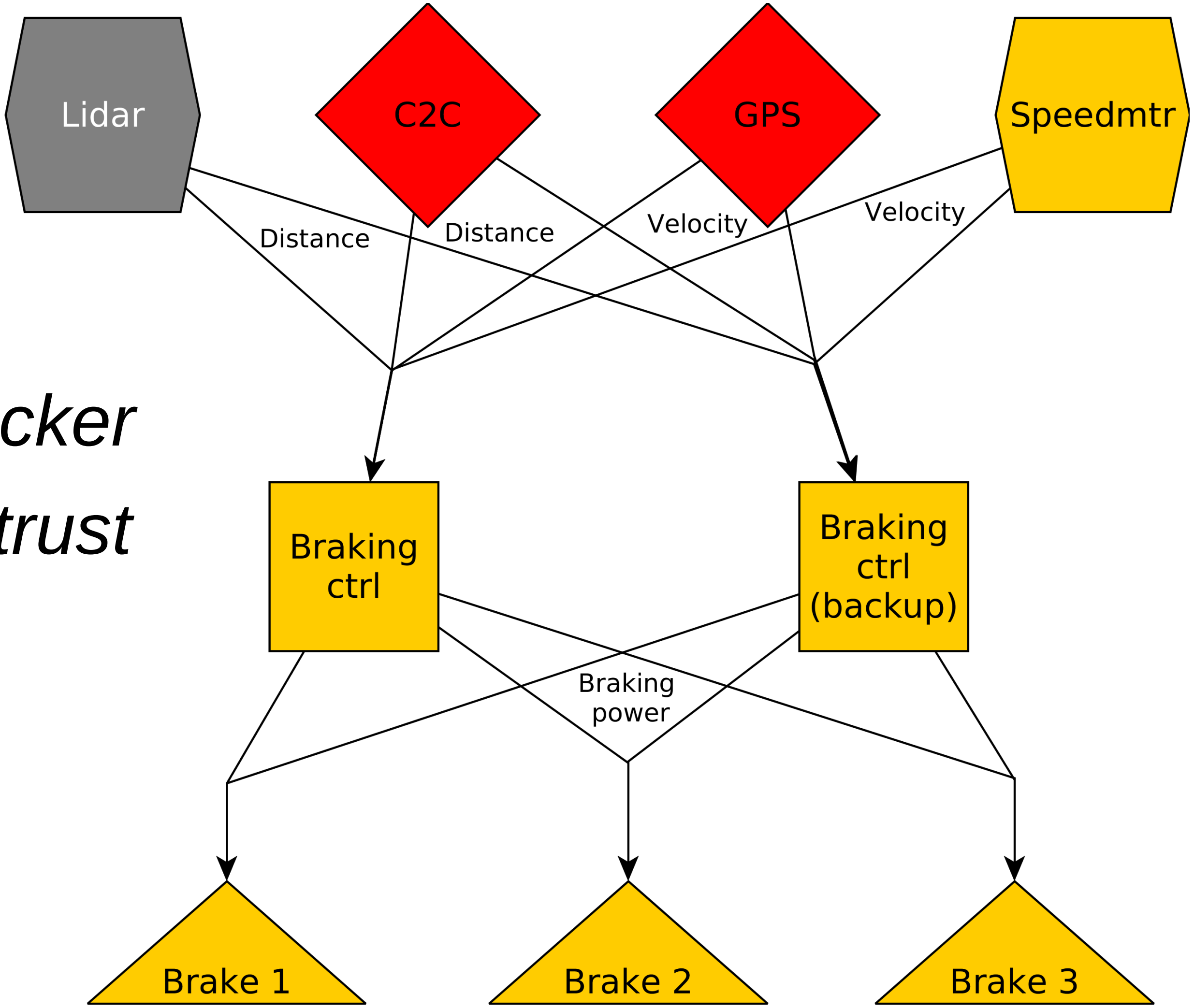
- Deterministic: first-order predicate logic
  - Implemented in the ACTIVE tool *[Ruchkin2014]* using the Z3 solver
  - Doesn't support second-order yet
- Probabilistic
  - Not fully designed, or implemented
  - Plan to:
    - Incorporate Probabilistic Computation Tree Logic (PCTL) in the language
    - Use probabilistic model checking tools: PRISM or MRMC

Detecting Vulnerability

$$\forall m \in \mathbb{M} \cdot |m.S_{trustworthy}|/|m.\mathbb{S}| \geq 0.5$$

Internal attacker

✖ *minimal trust*



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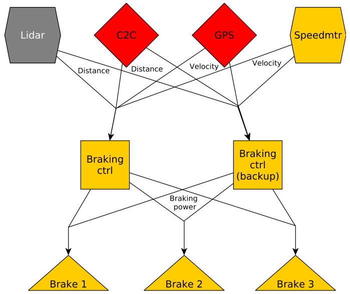
Limitations

- Generality
  - Approach applicable to other domains?
- Scalability & expressiveness
  - Will verification be feasible in other cases?
- Practicality
  - Is the up-front formal effort worth it?

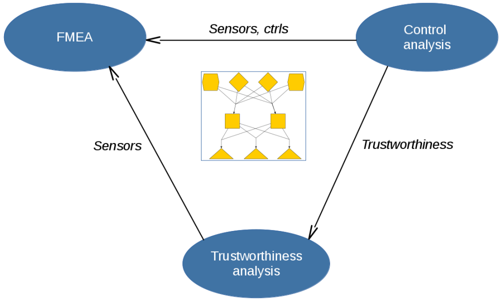
Future Work

- Richer contracts
  - Behavioral models for security
  - Probabilistic statements
  - Something else?
- Incorporating relevant domains
  - Suggestions?
- Validation
  - NOT building a self-driving car from scratch
  - Ideas?

Summary



- Described inter-domain vulnerabilities
- Demonstrated the analysis contracts approach
  - Specified analysis contracts
  - Determined dependencies
  - Verified deterministic assumptions



- *Future work:* more models and analyses, richer contracts, and validation

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ACTIVE tool: github.com/bisc/active
Car model: github.com/bisc/collision_detection_aadl

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AADL Example

```
system implementation avoidance_subsystem.impl
    subcomponents
        avoidance_process_A: process collision_threat_handler.A;
        avoidance_process_B: process collision_threat_handler.B;
        watchdog_process: process watchdog_proc.impl;
        vehicle_processor: processor basic_computing::real_time.one_ghz;
        vehicle_memory: memory basic_computing::ram.standard;
        vehicle_bus: bus basic_computing::basic_bus.standard;
        bus_driver: device basic_devices::bus_driver.standard;
        event_distributor: device basic_devices::event_distributor.standard;
    modes
        -- sensor failure modes
        nominal: initial mode;
        fail_mode_1: mode;
        fail_mode_2: mode;
        fail_mode_3: mode;

        nominal-[condition_1]->fail_mode_1;
        nominal-[condition_2]->fail_mode_2;
        nominal-[condition_3]->fail_mode_3;

        fail_mode_1-[condition_nominal]->nominal;
        fail_mode_2-[condition_nominal]->nominal;
        fail_mode_3-[condition_nominal]->nominal;
```

Probabilistic Contracts

- *Reliability assumption:* “probabilities of sensors not working are independent.”

$$\forall c_1, c_2 \in \mathbb{S} \cdot P(\neg c_1.\text{Avail} \mid \neg c_2.\text{Avail}) \leq P(\neg c_1.\text{Avail}) + \epsilon_{fail}$$

- *Security assumption:* “probabilities of sensors not working are dependent.”

$$\exists c_1, c_2 \in \mathbb{S} \colon P(\neg c_1.\text{Avail} \mid \neg c_2.\text{Avail}) \geq P(\neg c_1.\text{Avail}) - \epsilon_{trust}$$