Certifiable Distributed Runtime Assurance of Distributed Real-Time Systems

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Motivation

Distributed Real-Time Systems of great relevance to aerospace community

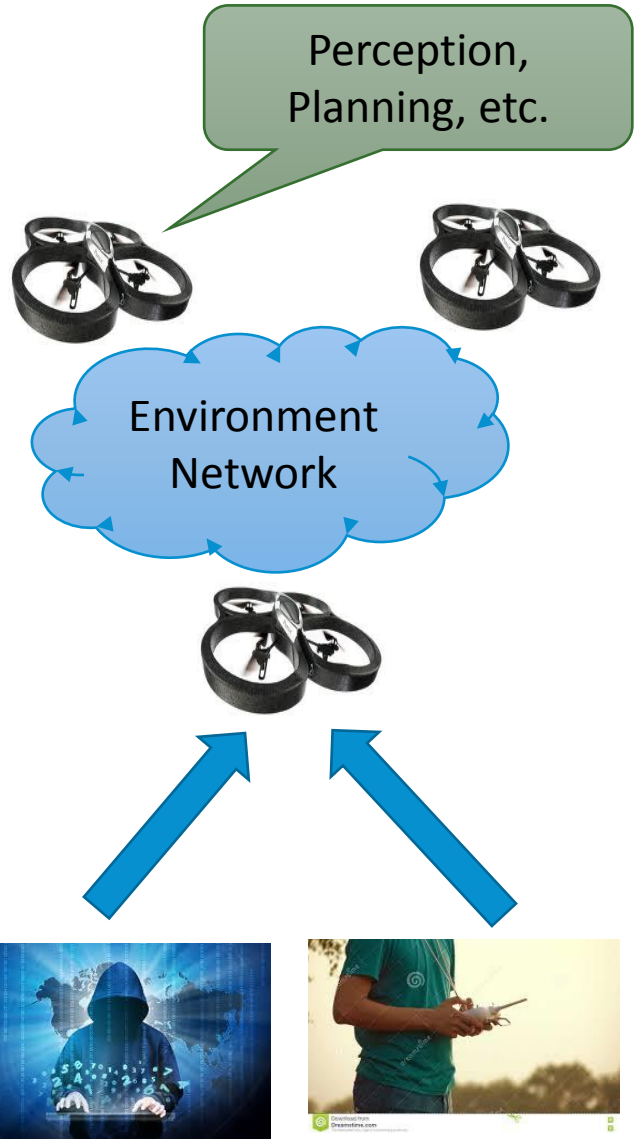
- Single aircraft with multiple sub-systems
- Multiple UASs coordinating to achieve mission

Operate in uncertain and unknown environments

- External uncertainty – normal and denied environments
- Internal uncertainty – sophisticated components with unpredictable behavior, e.g., machine learning

Safety-critical & hard real-time requirements

- Failures can be catastrophic
- How do we verify & certify?



Runtime Assurance

Suppose we want to assure that system S satisfies property Φ

Key Idea:

- Add a runtime "enforcer" to observe the behavior of S
- Step in and take enforcement action to prevent violation of Φ

Developed by AFRL & Barron Associates:

- http://www.mys5.org/Proceedings/2016/Day_1/2016-S5-Day1_1435_Schierman.pdf
- https://www.cs.indiana.edu/~lepike/pubs/RTA-CPS.pdf
- Enforcer referred to as the "reversionary system"

Prior Related Work (1)

Control theory – Simplex – CMU

- Seto, D., Krogh, B., Sha, L., and Chutinan, A., The simplex architecture for safe online control system upgrades, Proceedings of the American Control Conference, 1998.

Security Automata (Schneider) and Edit Automata (Ligatti et al.)

- Schneider, F. B., Enforceable security policies, ACM Transactions on Information and System Security (TISSEC), Vol. 3, No. 1, February 2000
- Ligatti, J., Bauer, L., and Walker, D., Edit automata: enforcement mechanisms for run-time security policies, International Journal of Information Security (IJIS), Vol. 4, No. 1-2, February 2005

Prior Related Work (2)

Runtime Verification – specific safety properties

- Kim, M., Viswanathan, M., Ben-Abdallah, H., Kannan, S., Lee, I., and Sokolsky, O., Formally specified monitoring of temporal properties, Proceedings of the 11th Euromicro Conference on Real-Time Systems (ECRTS '99), June 1999
- Havelund, K. and Rosu, G., Monitoring Programs Using Rewriting, Proceedings of the 16th International Conference on Automated Software Engineering (ASE '01), November 2001

Limitations:

- single properties over single components
- enforcers implementations not formally verified
- restricted enforcer scheduling model
- enforcer runs at the same level as S

Our Project: Certifiable Distributed Runtime Assurance (CDRA)

Problem: Runtime assurance (RA) is critical for complex non-deterministic systems.

Key idea: **monitor** the system and take preemptive action to avoid unsafe states; monitors are **simpler** more **verifiable**.

Challenges:

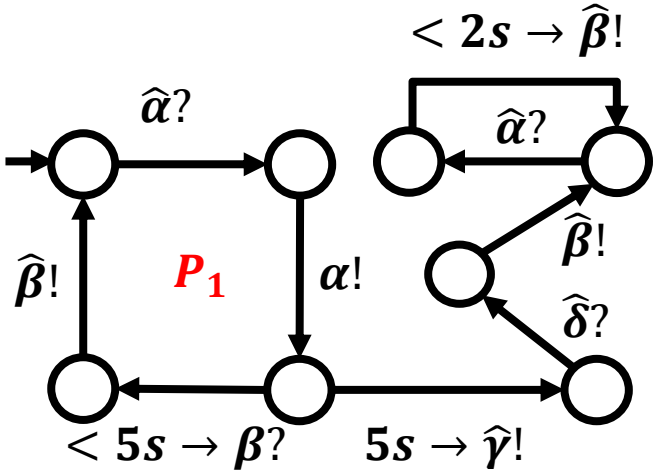
- **specifying** safety policies rigorously;
- **verifying** monitor (aka enforcer) implementations;
- preventing unsafe **inter-monitor** interactions (single-node and distributed systems);
- protecting monitors from being **circumvented**.

Solution: A combination formal policy specifications, software verification, compositional reasoning, and verified hardware-supported isolation.

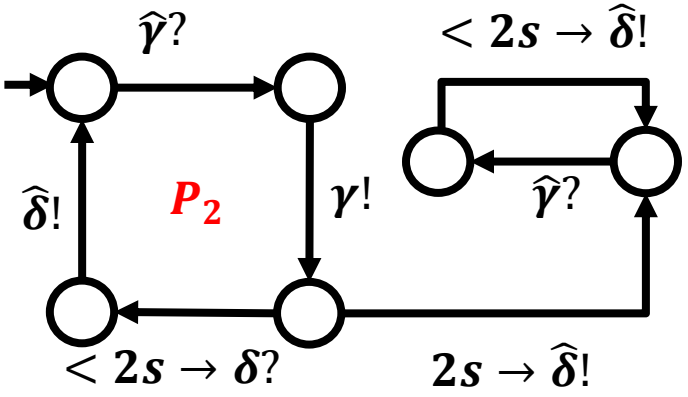
CDRA: Approach (1)

Prove $E_1 \preccurlyeq P_1$ and $E_2 \preccurlyeq P_2$ using software verification

Controller Policy



Logger Policy



Controller Enforcer Implementation (E_1)

Logger Enforcer Implementation (E_2)

Controller Component (C_1) $\{\alpha?, \beta!\}$ $\{\gamma?, \delta!\}$ **Logger Component (C_2)**

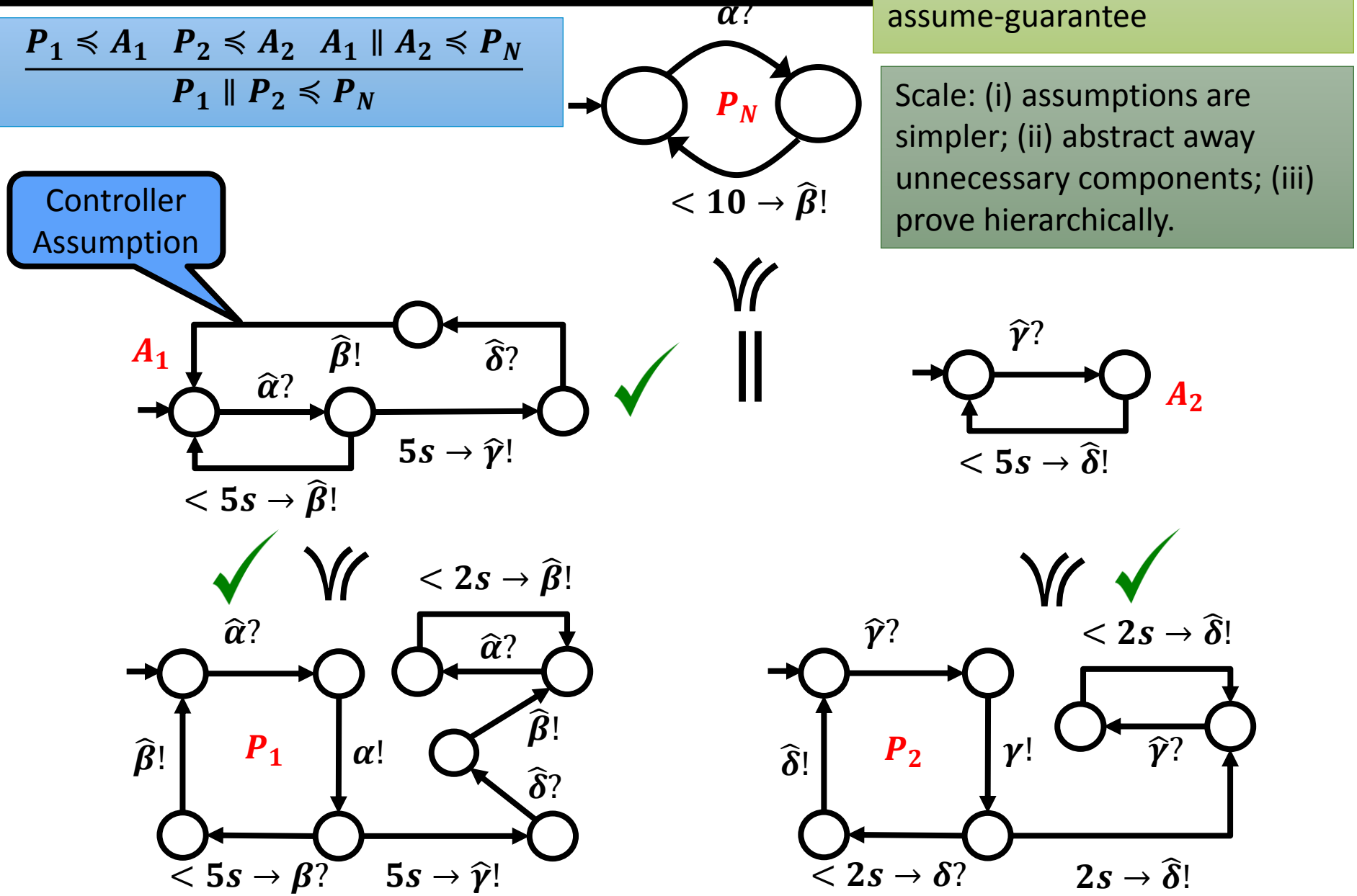
Node

CDRA: Approach (2)

Verify $P_1 \parallel P_2 \preccurlyeq P_N$ using assume-guarantee

$$\frac{P_1 \preccurlyeq A_1 \quad P_2 \preccurlyeq A_2 \quad A_1 \parallel A_2 \preccurlyeq P_N}{P_1 \parallel P_2 \preccurlyeq P_N}$$

Scale: (i) assumptions are simpler; (ii) abstract away unnecessary components; (iii) prove hierarchically.

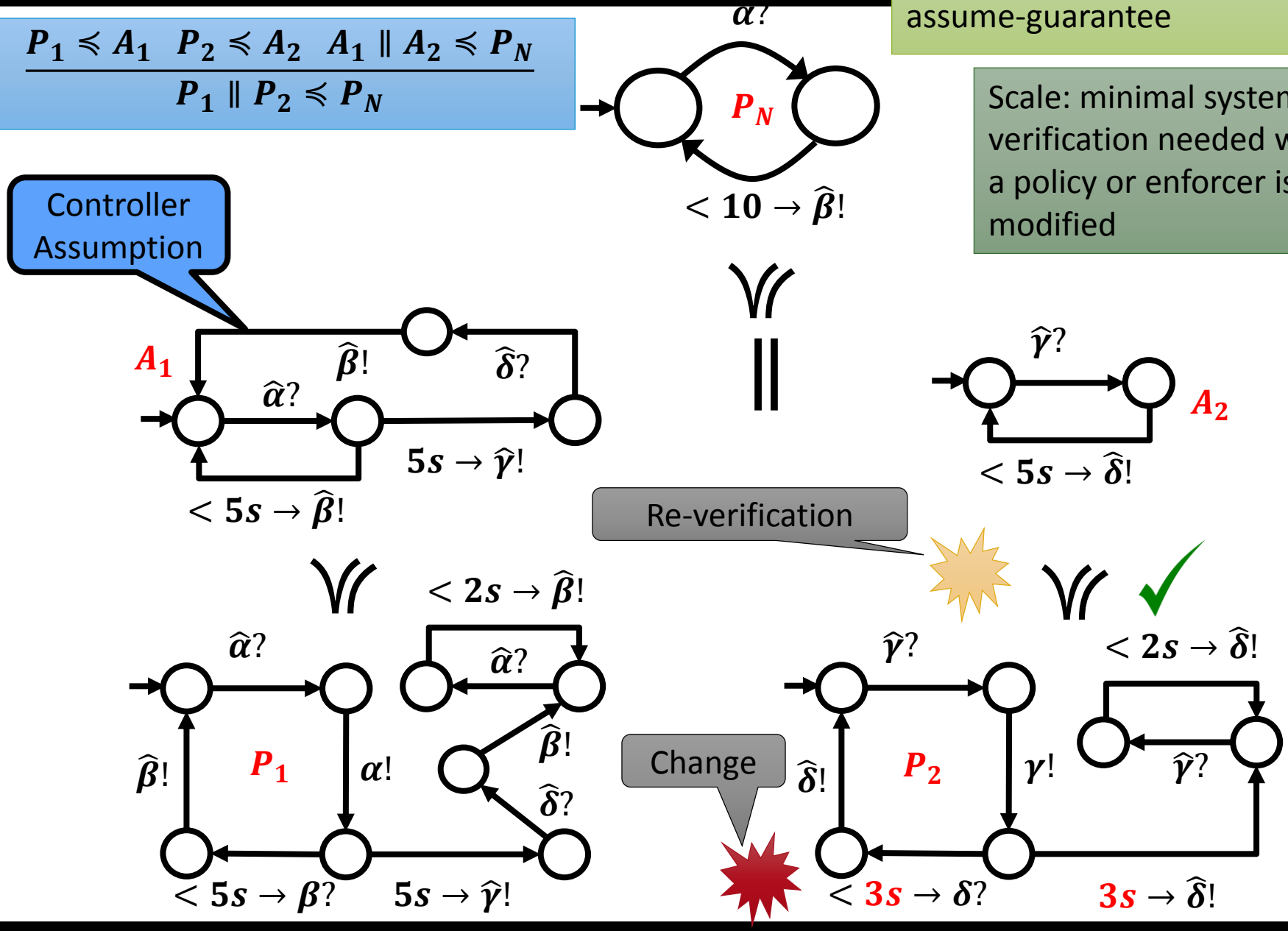


CDRA: Approach (3)

Verify $P_1 \parallel P_2 \preccurlyeq P_N$ using assume-guarantee

$$\frac{P_1 \preccurlyeq A_1 \quad P_2 \preccurlyeq A_2 \quad A_1 \parallel A_2 \preccurlyeq P_N}{P_1 \parallel P_2 \preccurlyeq P_N}$$

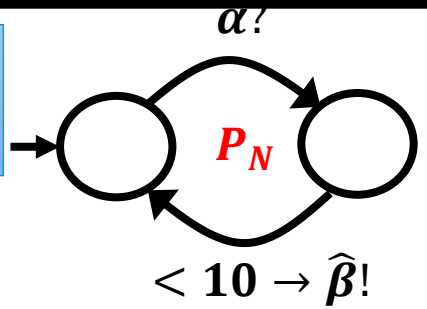
Scale: minimal system re-verification needed when a policy or enforcer is modified



CDRA: Approach (4)

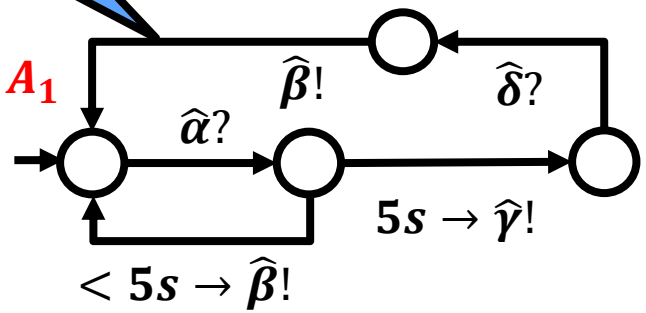
Verify $P_1 \parallel P_2 \preccurlyeq P_N$ using assume-guarantee

$$\frac{P_1 \preccurlyeq A_1 \quad P_2 \preccurlyeq A_2 \quad A_1 \parallel A_2 \preccurlyeq P_N}{P_1 \parallel P_2 \preccurlyeq P_N}$$



(i) Other (circular) rules exist; (ii) Challenges – (a) proving rule soundness; (b) finding right assumption.

Controller Assumption



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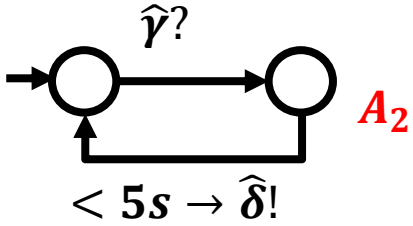
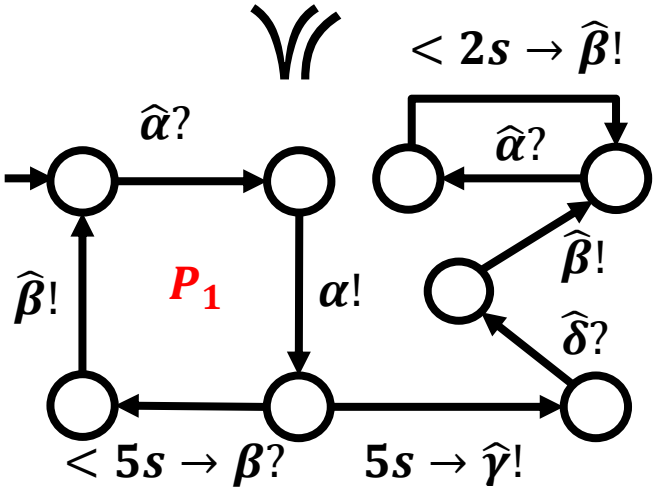
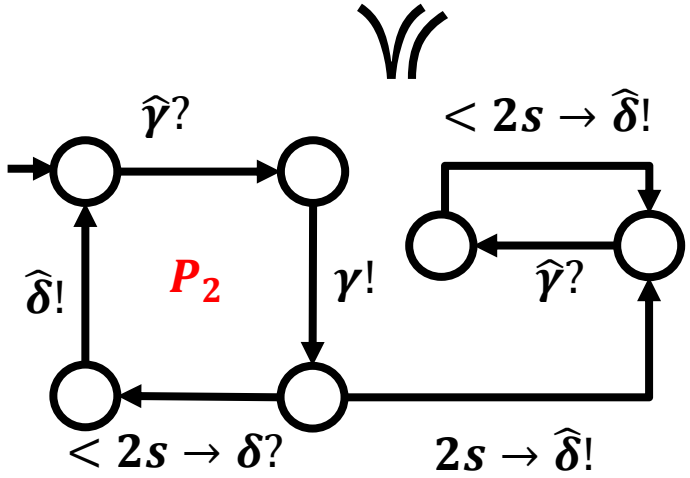
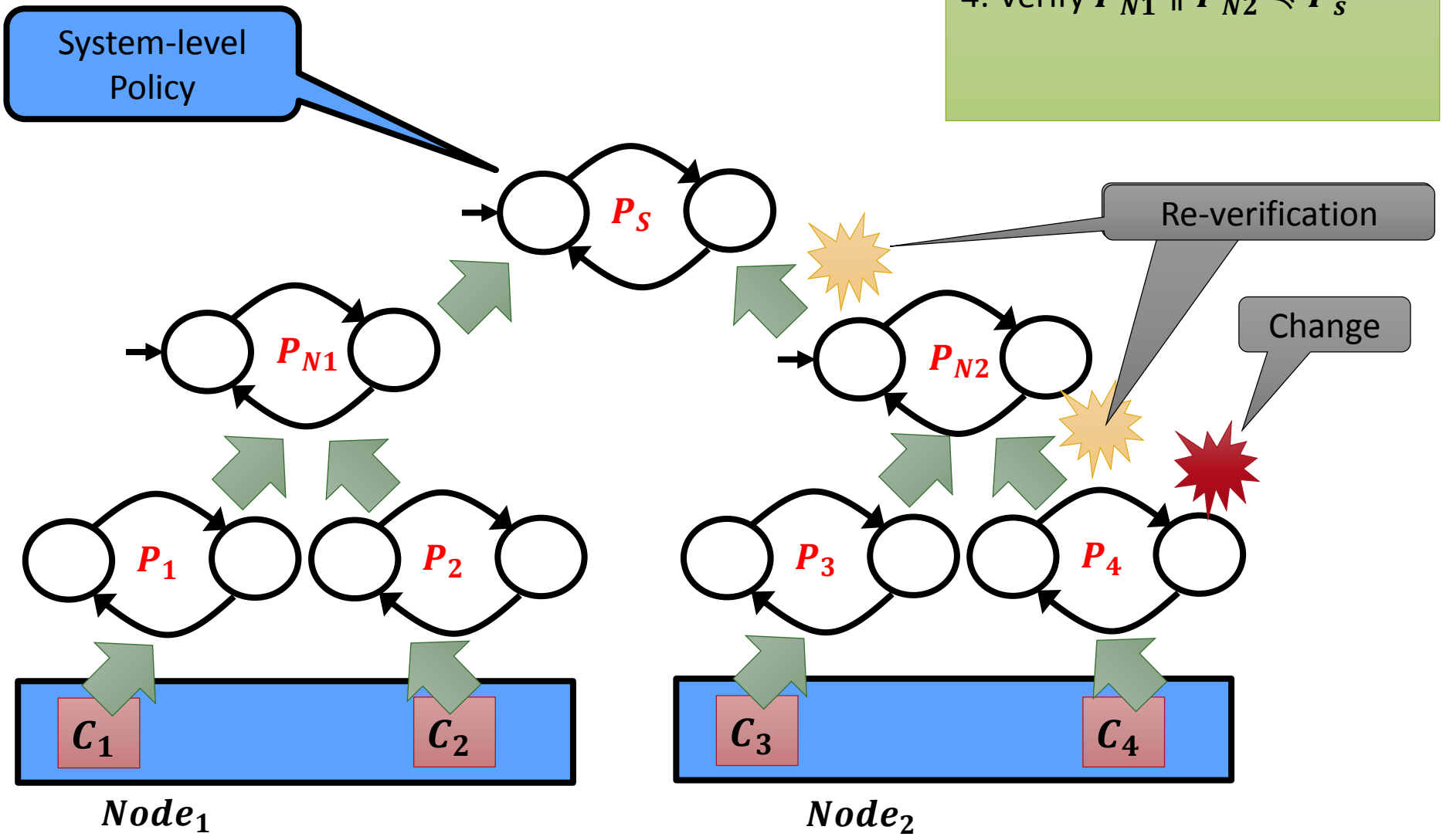






CDRA: Approach (5)

1: Verify $E_i \preccurlyeq P_i$
2: Verify $P_1 \parallel P_2 \preccurlyeq P_{N1}$
3: Verify $P_3 \parallel P_4 \preccurlyeq P_{N2}$
4: Verify $P_{N1} \parallel P_{N2} \preccurlyeq P_s$



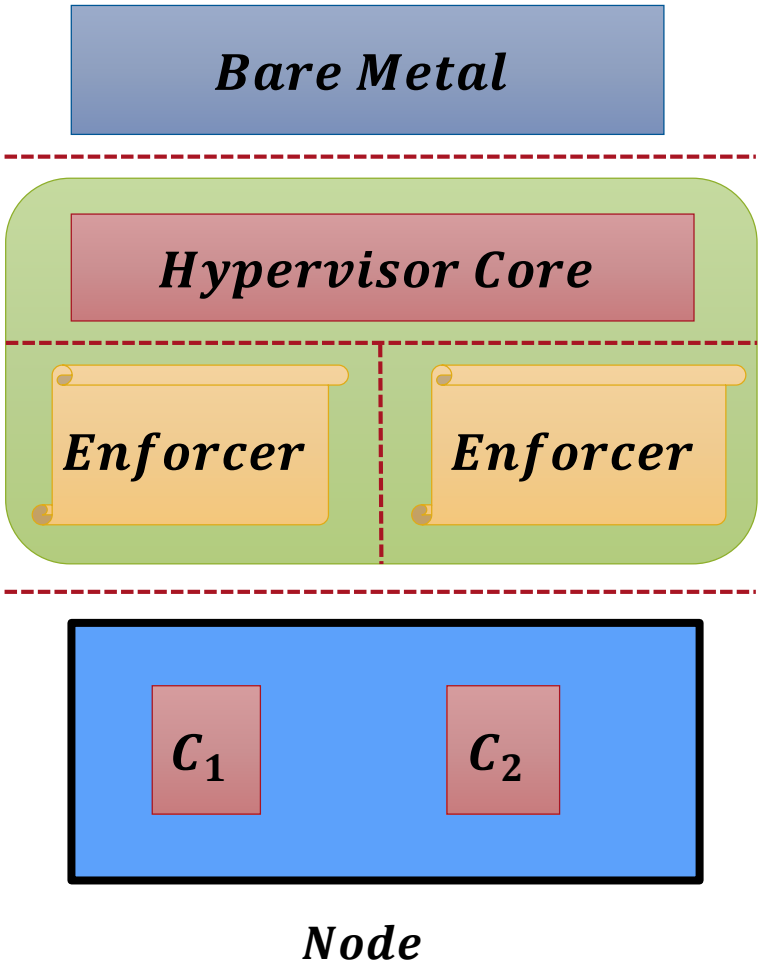
CDRA Approach (6)

Problem: Ensure that E_i is not circumvented. Inlining E_i in C_i will not work.

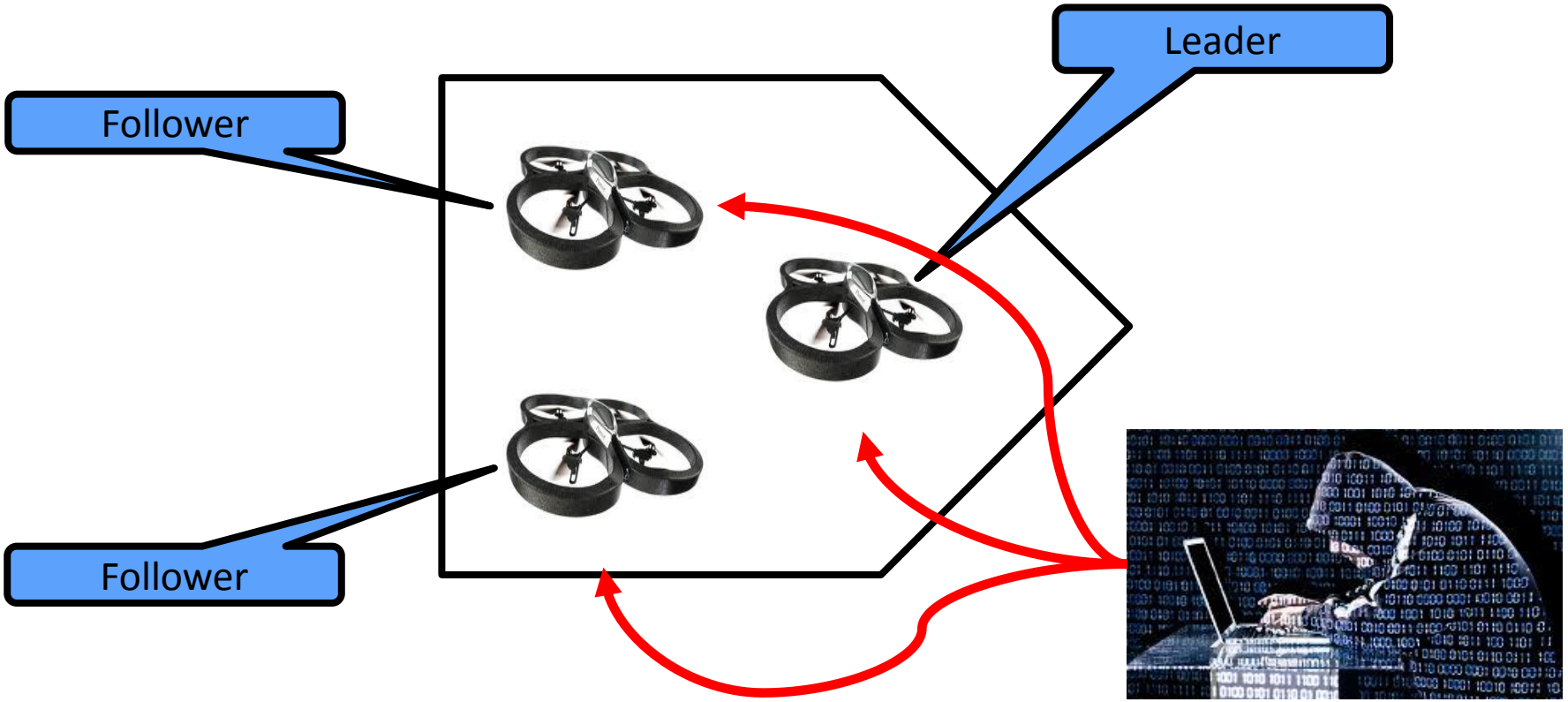
Solution: Use a hypervisor to execute E_i in an isolated environment. Prove correctness of isolation by verifying the hypervisor.

Build on XMHF: Amit Vasudevan, Sagar Chaki, Limin Jia, Jonathan M. McCune, James Newsome, Anupam Datta: *Design, Implementation and Verification of an eXtensible and Modular Hypervisor Framework.* IEEE Symposium on Security and Privacy 2013: 430-444. Many security- relevant applications already developed on top of XMHF. See references.

Challenges: Performance, Correctness

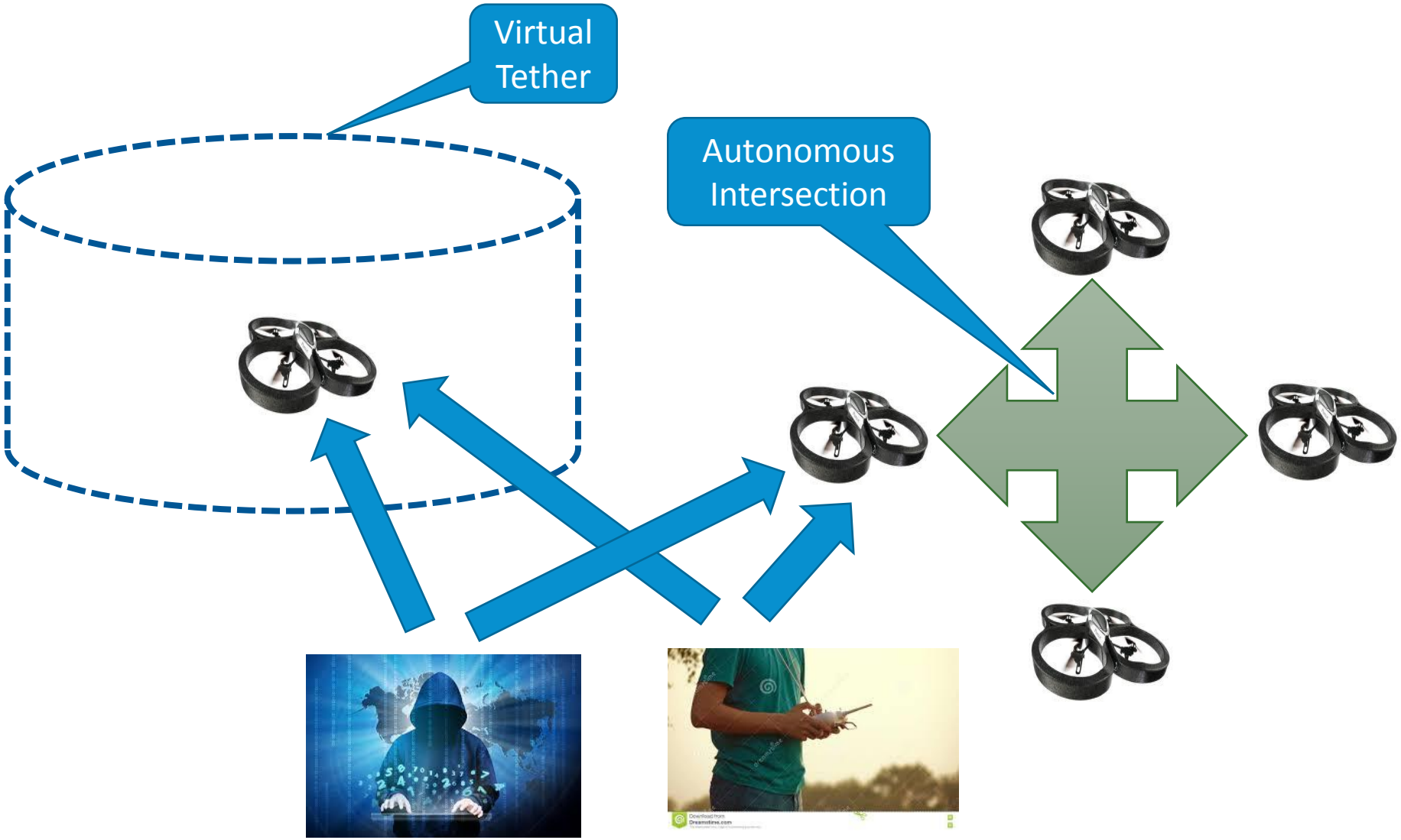


CDRA Validity



Demonstrate verified runtime assurance on a realistic scenario.
Give red team full control over applications (e.g., root access to OS)
Initially in simulation, eventually on a hardware platform.

CDRA Challenge Problems

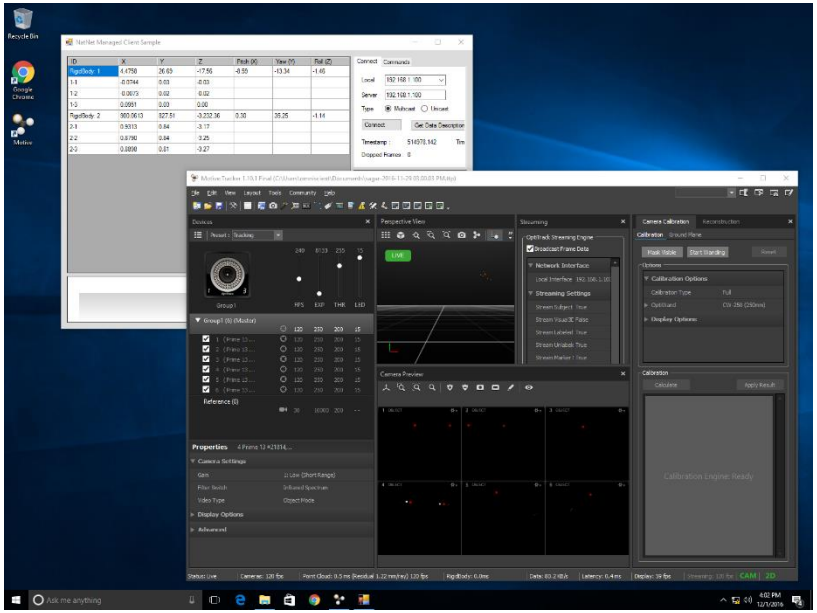


CDRA Testbed

Parrot Minidrones

Optitrack Localization

Optitrack Localization



ETH QuadCopter

Questions?