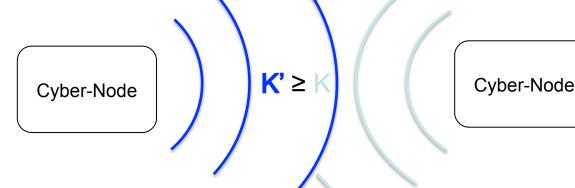
A Logical Framework for Self-Optimizing Networked Cyber-Physical Systems

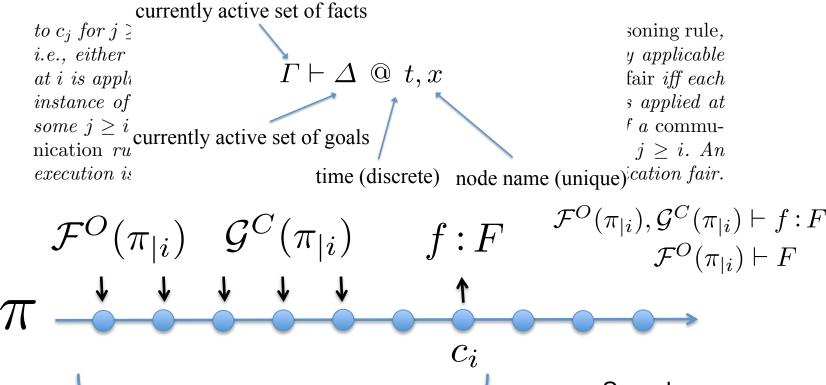
An Application Framework for Networked CPS

- Based on new loosely-coupled distributed computing model: Partially Ordered Knowledge Sharing
- Inspired by our earlier work on delay-/disruption-tolerant networking (DTN)
- Minimal assumptions on network connectivity (can be very unreliable)
- Works with dynamic topologies, network partitions, and mobile nodes
- Designed for heterogeneous networking technologies and heterogeneous nodes
- Partial order allows the network to replace obsolete or subsumed knowledge
- Global consistency is not enforced (impossible in challenging environments)
- Avoids strong non-implementable primitives, e.g. transactions
- Locally each cyber-node uses an event-based model with local time
- Events are local, but knowledge can be shared and cached in the network
- Each cyber-node can have attached cyber-physical devices
- Framework supports
- model-based simulation
- probabilistic analysis algorithms
- real-world deployment/execution
- visualization of simulated NCPS



Distributed Logic for Declarative Control

- Truly distributed logical framework with explicit proof objects
- Cyber-predicates enable interaction with the physical world
- Facts and goals treated on an equal footing
- Covers entire spectrum between autonomy and cooperation
- Tested with abstract mobility model and Stage multi-robot simulator
- Soundness, Completeness, and Termination Conditions



holds because derived atoms that appear in π are entailed by previous observa-Soundness tions and controls of π , π entailment on derived atoms implies entailment of η . Horn clause logic.

ThéoFéns F (Source addition a derived late f, f is containing covered in π there is some i and methave for F ($\pi_{|i}$), by F ($\pi_{|i}$), the following covered of countlegences is that if we that F for $\pi_{|i}$, by F ($\pi_{|i}$), the following coveres the following covered of $\pi_{|i}$) is contained in $\pi_{|i}$ in the following covered of $\pi_{|i}$ ($\pi_{|i}$) is contained in $\pi_{|i}$ ($\pi_{|i}$) is contained in $\pi_{|i}$ ($\pi_{|i}$) in the following covered of $\pi_{|i}$ ($\pi_{|i}$) is contained in $\pi_{|i}$ ($\pi_{|i}$) is contained in $\pi_{|i}$ ($\pi_{|i}$) in $\pi_{|i}$ ($\pi_{|i}$) in the following covered in $\pi_{|i}$ ($\pi_{|i}$) is contained in $\pi_{|i}$ ($\pi_{|i}$) in $\pi_{|i}$ ($\pi_{|i}$) in $\pi_{|i}$ ($\pi_{|i}$) is contained in $\pi_{|i}$ ($\pi_{|i}$) in $\pi_{|i}$ ($\pi_{|i}$) in $\pi_{|i}$ ($\pi_{|i}$) is contained in $\pi_{|i}$ ($\pi_{|i}$) ($\pi_{|i}$) in $\pi_{|i}$ ($\pi_{|i}$) ($\pi_{|$ of F will be eventually covered in the execution. The completeness theorem Presenterenterent trainass this disguination with sufficient constraints for conspleteness to hold. The tater is oken no to par firs howi pro Lenerablid, Parivability in the total for the pair, instantour problem in the information of \mathcal{F} is entangled factored for the problem in the pair of the pair of the problem in the pair of the p

split into two cases depending whether the final rule in the Horn clause derivation Proof. We show $F \models F$ by cases on f. If $F \models F$ is $B_{-}F_{0}$: $\sigma(G)$ then $\vdash \sigma(G)$ is a forwards of backwards rule. This is needed to account for the requirement by definition of derived facts. If f:F is O(F):F we have $O(F) \vdash O(F)$. If f:F is that there must be a goal that unifies with a backwards rule conclusion of Q is f(G), then by GOM and f:F is O(F):F we have $O(F) \vdash O(F)$. If f:F is f(f):F is $O(F) \vdash f$ in Ω , then by GOM accurate the first in the backwards rule conclusion of Q is f(G), with f:F is $O(F) \vdash G(G)$ in Ω , then by GOM applies the form only applies the first of G is $f(f):F \vdash G(G)$. The first in the backwards case, the theorem only applies have $F \vdash G(G)$ and $F \vdash \sigma(Q)$, applying clause l.

remma 2 (Derivations, are deriva

 $\Gamma \vdash \Delta @ t, x$ $\frac{\underline{}}{\Gamma\vdash\Delta,\mathtt{C}(G):G@t',x} \quad \text{if } G =$

 $\frac{\varGamma\vdash\varDelta\ @\ t,x}{\varGamma, \mathsf{O}(F):F\vdash\varDelta\ @\ t',x} \ \ \text{if}\ F$

 $\frac{\varGamma,f:F\vdash\varDelta\ @\ t,x}{\varGamma\vdash\Delta\ @\ t',x} \quad \text{if}\ f:F\prec$

 $\frac{\varGamma\vdash\varDelta,g\!:\!G @ t,x}{\varGamma\vdash\varDelta @ t',x} \quad \text{if } g\!:\!G\prec$

 $\Gamma_x \vdash \Delta_x @ t_x, x \quad \Gamma_y, f : F \vdash$ $\Gamma_x, f: F \vdash \Delta_x @ t'_x,$ if $x \neq y, t'_x \geq t_y$, and f: F is f $\Gamma_x \vdash \Delta_x @ t_x, x \quad \Gamma_y \vdash \Delta_y, g$

 $\Gamma_x \vdash \Delta_x, q : G @ t'_x,$ if $x \neq y, t'_x \geq t_y$, and g: G is f

 $\Gamma \vdash \Delta, g : G @ t, x$ $\overline{\Gamma, \mathtt{B}_{\sigma}(g) : \sigma(G) \vdash \Delta, g : G @ t'}$ if G is a built-in goal with a so

 $\Gamma, f_1: \sigma(P_1), \ldots, f_n: \sigma(P_n)$ $\Gamma, f_1 : \sigma(P_1), \ldots, f_n : \sigma(P_n), f$ if $l: P_1, \ldots, P_n \Rightarrow Q$ is a clause $f = l_{\sigma}(f_1, \ldots, f_n), \, \sigma(Q)$ is a factor $\Gamma, f_1: \sigma(P_1), \ldots, f_{j-1}: \sigma($ $\overline{\Gamma, f_1: \sigma(P_1), \ldots, f_{j-1}: \sigma(P_{j-1})}$ if $l: P_1, \ldots, P_n \Rightarrow Q$ is a clause

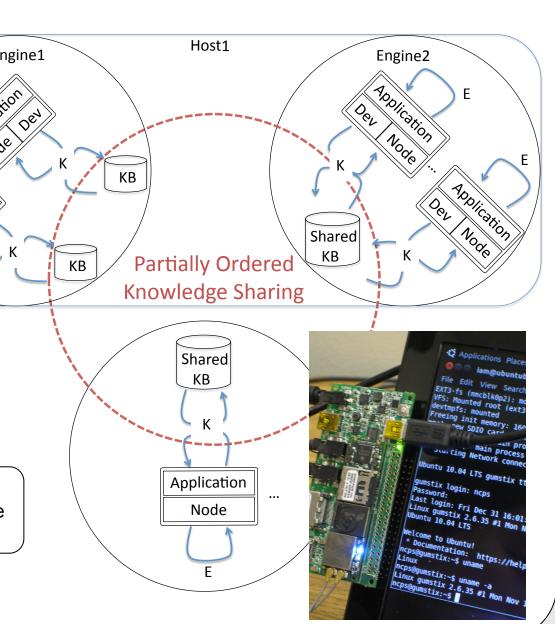
 $g = l_{\sigma}^{-1}(f_1, \dots, f_{j-1}), \, \sigma(P_j)$ is $\Gamma, f_1: \sigma(P_1), \ldots, f_n: \sigma(P_n)$ $\overline{\Gamma, f_1: \sigma(P_1), \ldots, f_n: \sigma(P_n), f}$ if $l: P_1, \ldots, P_n \Rightarrow Q$ is a clause

 $f = l_{\sigma}(f_1, \dots, f_n; g'), \ \sigma(Q) = 0$ $\Gamma, f_1: \sigma(P_1), \ldots, f_{j-1}: \sigma($ $\overline{\Gamma, f_1: \sigma(P_1), \ldots, f_{j-1}: \sigma(P_{j-1})}$

if $l: P_1, \ldots, P_n \Rightarrow Q$ is a clause $g = l_{\sigma}^{-1}(f_1, \dots, f_{j-1}; g'), \, \sigma(Q)$ $\Gamma \vdash \Delta @ t, x$ $\overline{\Gamma \vdash \Delta @ t', x}$

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with Contributions from Jinwoo Kim (Seoul National Univ.), Vincent Wang (UPenn), Tim McCarthy (SRI)



$= p_c(t, \ldots)$ is a cyber-goal	(Control)	
$= p_c(t, \ldots)$ is a cyber-fact	(Observation)	
$\prec \Gamma, \Delta$	$({\sf Replacement1})$	
$\prec \Gamma, \Delta$	$({\sf Replacement2})$	
$\frac{\Delta_y @ t_y, y}{x}$ fresh at x .	$({\sf Communication1})$	
$\begin{array}{c} :G @ t_y, y \\ x \\ \hline \\ \text{fresh at } x \end{array}$	(Communication2)	
$\overline{f,x}$ olution $\sigma(G)$ such that $\mathtt{B}_{\sigma}(g)$: $\sigma(G)$:	(Built-in) is fresh.	
$\begin{array}{l} \underline{\sigma}_{n} \end{pmatrix} \vdash \underline{\Delta} @ t, x \\ \hline \sigma(Q) \vdash \underline{\Delta} @ t', x \\ e \text{ from } \Omega_{f}, \end{array}$	(Forward1)	
act, and $f: \sigma(Q)$ is fresh. $(P_{j-1}) \vdash \Delta @ t, x$ $(I) \vdash \Delta, g: \sigma(P_j) @ t', x$ e from $\Omega_{\rm f}$,	(Forward 2)	
is a goal, and $g: \sigma(P_j)$ is fresh. $\sigma(Q) \vdash \Delta, g': G' @ t, x$ $: \sigma(Q) \vdash \Delta, g': G' @ t', x$ e from $\Omega_{\rm b}$,	(Backward1)	
$\sigma(G'), \ \sigma(Q) \text{ is a fact, and } f : \sigma(Q) \text{ is}$ $(P_{j-1}) \vdash \Delta, g' : G' @ t, x$ $(P_j) \vdash \Delta, g' : G', g : \sigma(P_j) @ t', x$ e from $\Omega_{\rm b}$,	s fresh. (Backward2)	
$\sigma(G'), \sigma(P_j)$ is a goal, and $g : \sigma(P_j)$ is fresh.		
	(Sleep)	

Networked Quadricopter Testbed

- Quadricopters (and their components) become devices in the cyber-application framework

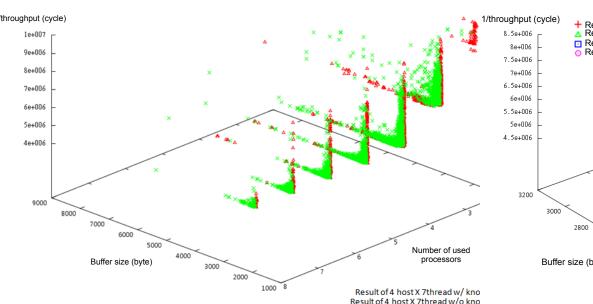
- Currently experimenting with vision-based localization for indoor-usage (see pictures below)



Four quadricopters before the launch

Parallel and Distributed Optimization

- Distributed and parallel meta-heuristic framework combining an existing mature sequential optimization framework (Opt4J) with a loosely coupled distributed island model for scalable parallelization
- The parallelism is transparently provided by the cyber-framework cyber-nodes cooperate by emitting waves of knowledge, which interfere until all local solutions asynchronously converge to a global solution
- Optimization fits well into the partially ordered knowledge-sharing model
- Replacement order is defined by either
- single objective function (solution fitness) or multiple objective functions (Pareto optimality)
- Algorithm: population based meta-heuristic optimizer utilizing the island model
- Case study: design space exploration of an embedded multimedia system
- Key features: scalability and robustness in the optimization problem
- Optimizer performance is studied on Internet-wide testbed (Planet Lab)
- Possible next steps:
- Combining optimization and declarative control
- Use of weighted/quantitative/probabilistic logic
- A small-scale real-world deployment (e.g., formation flight of quadricopters)



Knowledge-sharing leads to better solutions within a limited time.

Distributed Hosts *Cyber Engine at Cyber Host2* Cyber Engine at Cyber Host1 Cyber Node (Thread) Cyber Node (Thread) 000 000 000 Island Island sub-population sub-population Sharing *K* among Cyber Nodes Sharing K among Cyber Nodes Sharing K among Cyber Hosts K: Knowledge which includes dominant individuals Kernel Start 1) Load Opt4J modules and configuration file 2) Initialize modules Run modules to configured migration period Migration Post individuals condition is from archive satisfied? Result of (4 hosts) X (7 threads), local population size: 10 Result of (2 hosts) X (7 threads), local population size: 20 Result of (2 hosts) X (7 threads), local population size: 20 Result of (2 hosts) Result of (1 hosts) X (7 threads), local population size: 400 Result of (1 hosts) X (1 threads), local population size: 280 Shared Handle incoming Knowledge individuals Base Snapshot condition is Take snapshot satisfied? erminatior Buffer size (byte) condition is Number of used satisfied? Convergence Knowledge Solutions from parallel and sequential ----> Solution Knowledg Report execution represent similar quality.



• Quadricopters are a very interesting class of cyber-physical devices (equipped with many sensors and actuators including cameras) • Networked quadricopters will allow us to perform collaborative tasks (e.g. formation flying, distributed sensing, monitoring)

• Currently controlled from a network of netbooks on the ground (each node can control one or multiple quadricopters) Can be equipped with gumstix SBC and additional devices (e.g. GPS, digital compass) for more autonomy



Four quadricopters controlled by the cyber-application framework



Vision-based localization experiment (utilizing Kinect 3D camera)