Localization and System Services for SpatioTemporal Actions in Cyber-Physical Systems

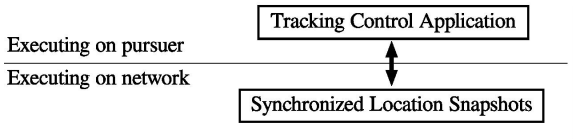
Prof. Anish Arora (Co-PI: Ohio State University), Prof. Rajesh Gupta (Co-PI: UC San Diego), Dr. Ryo Sugihara (UC San Diego)

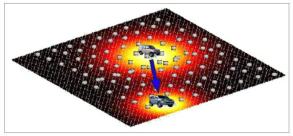
A Focus on Deterministic Properties

Sensed data is typically profiled in terms of statistical properties
- Focus is on efficiency of learning/testing of statistics

But for CPS applications, safe/critical operation often demands deterministic properties
- Our focus is on worst-case bounds on spatiotemporal properties
  i.e., network time, node location, state latency / error/ rate

Example: Pursuer-Evader Control System





Control Properties Depend on Deterministic Guarantees

For single-pursuer single-evader catch-me game,
Nash equilibrium strategy exists *provided*
deterministic guarantees exist on snapshot latency, error, and rate

Theorem:

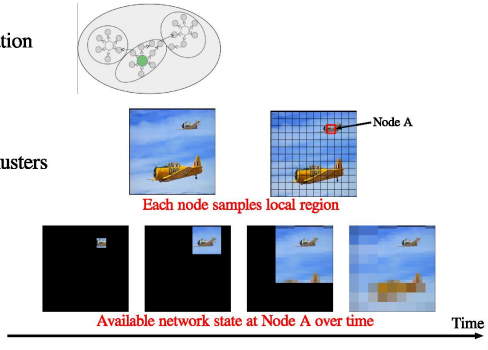
Given
- distance $d_{pe}(t)$ between pursuer p & evader e
- speed ratio $\alpha = v_p/v_e$
- error $z(t)$ in distance estimate
- staleness $\delta(t)$ in the state snapshot
- synchronization interval $r(t)$ between snapshots

Eventual catch guaranteed if there exists $k > \frac{\alpha+1}{\alpha-1}$ s.t.
- distance sensitive latency: $\delta(t) < \frac{d_{pe}(t)}{v_e}\left(1 - \frac{\alpha+k+1}{\alpha k}\right)$
- distance sensitive error: $z(t) < \frac{d_{pe}(t)}{k}$
- distance sensitive rate: $r(t) < \frac{d_{pe}(t)}{v_p}\frac{k+1}{k}$

Algorithms and Techniques for System Services with Deterministic Accuracy Guarantee

- Distance Sensitive Snapshot Service

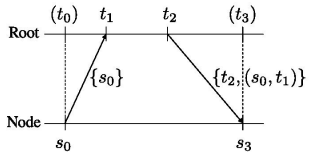
- Clustering
  + Solid disk clustering with or without localization
  + Stretch factor gives local healing
  + Extended to log(N) levels
- Scheduling
  + Aggregate and disperse data along trees in clusters
  + At each level
    - Clusterhead compresses data into m bits
    - Summary dispersed to all nodes in cluster & its neighboring clusters
  + Pipelined implementation
    - Nodes generate fresh data as soon as previous data out of level-1 clusters



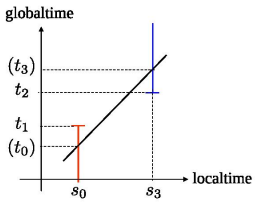
- Clock Synchronization

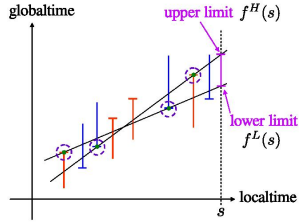
- Use causality in messaging to obtain constraints on global time
- Synchronization error bounds derived from multiple constraints

Root-Node case:



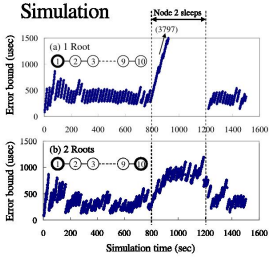
Constraints:
$f(s_0) = t_0 < t_1,\ f(s_3) = t_3 > t_2$



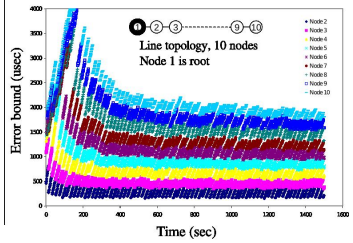


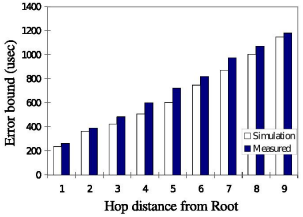
Guarantee: $f^L(s) \le f(s) \le f^H(s)$

Simulation



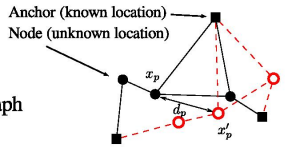
Testbed experiments





- Sensor Localization

- Sensor localization as (nonconvex) optimization problem
- Upper bound of localization error by SDP relaxation

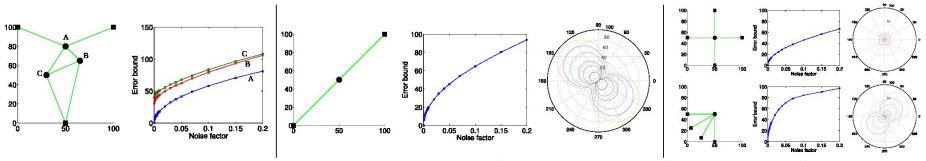


Formulation idea: Distance of nodes in two different realizations of a graph

Maximize $||x'_p - x_p|| (= d_p)$

s.t. - distance between nodes: $||x_i - x_j||^2 = d_{ij}^2, \forall (i,j) \in E_n$ $\quad ||x'_i - x'_j||^2 = d_{ij}^2, \forall (i,j) \in E_n$

- distance between node and anchor: $||x_j - a_k||^2 = d_{jk}^2, \forall (j,k) \in E_a$ $\quad ||x'_j - a_k||^2 = d_{jk}^2, \forall (j,k) \in E_a$



Iterative algorithm for large networks
- Further relaxation: Solve SDP for subgraphs
- Increase the size of subgraph to improve error bounds