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

Minyoung Kim, Mark-Oliver Stehr, Carolyn Talcott
SRI International

A Logical Framework for Networked CPS

Unifying framework
• A rigorous logical and semantic framework with degrees of satisfaction
• Unifying quantitative and qualitative reasoning and optimization
• Support robust distributed operation via knowledge sharing
• Accounting for incomplete information and uncertainty

Balance between autonomy and cooperation
• Distributed notion of goals, proofs, and proof robustness
• No need to rely on the existence or connectivity of other nodes

Distributed cross-layer strategies
• Sufficiently good solutions with acceptable resource consumption
• Sharing knowledge about solutions is essential

Logical Control and Optimization Strategy

Example: Interest-driven operation of Networked CPS as a logical strategy
• The following goal is injected at the node $r$ and disseminated through the network
  \[ \text{Motion}(a, t) \lor \text{Noise}(a, t) \Rightarrow \exists I : \text{Image}(I, a, t, t + \Delta t) \land \text{Delivered}(\text{Extract}(\text{Abstract}(I)), r) \]

  A node in area $a$ generates a fact \text{Motion}(a, t), leading to the simplified goal
  \[ \text{Image}(I, a, t, t + \Delta t) \land \text{Delivered}(\text{Extract}(\text{Abstract}(I)), r) \]

  Now, an image $i$ is taken, leading to the remaining goal
  \[ \text{Delivered}(\text{Extract}(\text{Abstract}(i)), r) \]

  The abstraction \text{Abstract}(i) \rightarrow i' can be performed locally (but feature extraction cannot), yielding
  \[ \text{Delivered}(\text{Extract}(i'), r) \]

  A more powerful node can perform the computation \text{Extract}(i') \rightarrow i'', resulting in
  \[ \text{Delivered}(i'', r) \]

  A goal, which can be proved by routing it toward $r$ (increasing degree of satisfaction),
  where it is finally realized by the delivery action \text{Delivered}(i'', r)

Robustness and composability via abstraction
• Abstract representation of solution regions via symbolic constraints
• Inherent parallelism and fault tolerance by coordinated actions of individual nodes
• Near-optimal and robust solutions by distributed cooperative constraint refinement

Distributed goal refinement and proof construction by strategy
• Establish intermediate goals if goal cannot be reached by a single action
• Explore multiple solution regions by combining symbolic reasoning with sampling and randomization techniques

Distributed model adaptation by observation and exploration
• Passively accumulated knowledge by observations
• Active exploration via physical actions

Test Case: Self-organizing Team of Mobile Robots

Objectives and challenges
• System may assemble and adapt on the fly for a given purpose (e.g., distributed sensing) in a resource- and situation-aware fashion
• Challenges include
  • Wide spectrum of network characteristics with mobility, delay, and disruption
  • Failure, uncertainty, partial knowledge, and stale information
  • Resource/energy constraints and tradeoffs
  • Problem requires true cross-layer solutions, more general than traditional top-down (e.g., planning) and bottom-up (e.g., neighbor discovery) approaches
  • Network topology can morph and expand driven by goals
  • Pooling resources is possible and even essential for the solution
  • Adaptive model of environment (e.g., map) is needed for intelligent control