Perception-Based, Reactive, Temporal-Logic Planning for Autonomous Deck Operations

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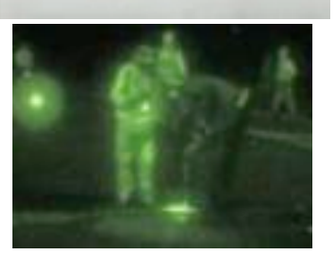
Project Quad Chart

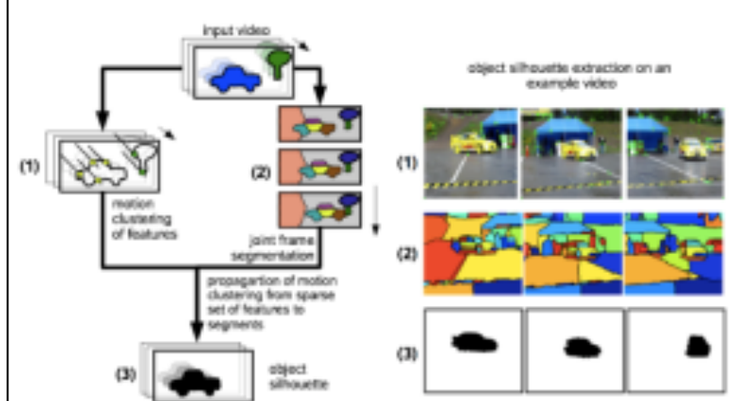
Goal: Enable autonomous navigation for the ground operation of unmanned vehicles on aircraft carrier decks.

Technical objectives: Develop methods and automated tools for the formal specification and synthesis of reactive autonomy protocols for operations in constrained and uncertain environments under sensing/perception limitations and imperfections.



Approach – Perception: Using perception to extract semantics with (probabilistic) uncertainty

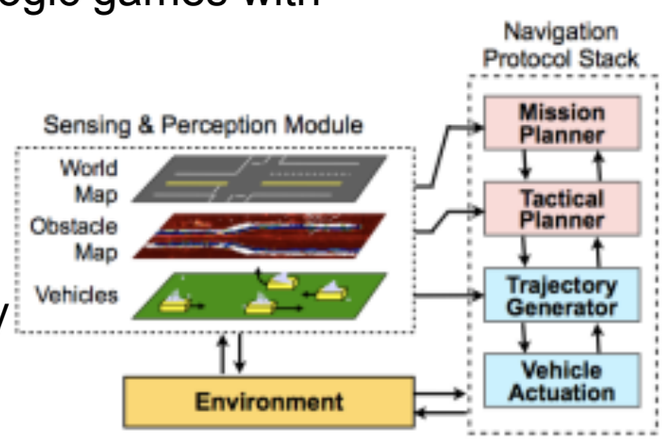
- Semantic mapping
- Segmentation and semantic mapping of moving objects



Semantic mapping refers to tagging each object in vehicle's environment with a label and its pose. The perception module translates sensing information to semantic descriptions.

Approach – Synthesis: Reactive synthesis with limited sensing & imperfect perception

- Synthesis and temporal logic games with partial information
- Synthesis in stochastic domains with imperfect information
- Coping with the computational complexity



Reactive planning merges hierarchical autonomy protocols with uncertainty representations from perception.

Schedule, evaluation & transition:

FY 14	•Perception for static objects •Protocols for joint planning and information gathering	Develop a case study with typical deck layout, operation scenarios, rules & constraints, sensing modalities & limitations. Update each year to align with research.
FY 15	•Temporal persistence & dynamic objects in perception •Integrate probabilistic perception uncertainty into the protocols	
FY 16	•Perception: evaluation with various vehicle models & metrics •Synthesis: computational complexity reduction	

Ufuk Topcu

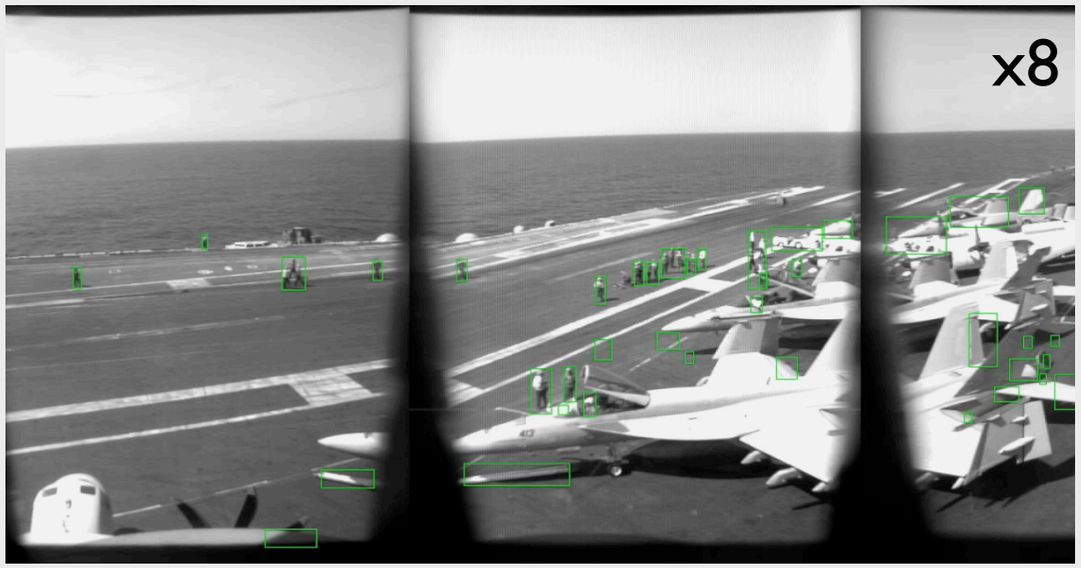
Planning on the deck environment

Dynamic, uncontrolled objects around UAV

Relatively structured and constrained environment

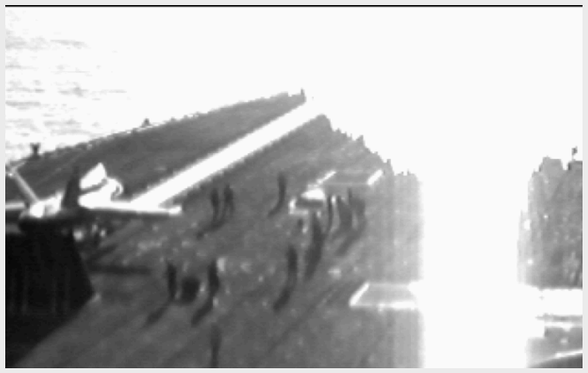
Well-established rules, temporal ordering of events

Safety-critical



Sign- and sensing-rich but…

- Low lighting, blooming, sun glare
- Steam
- Emission control and signature management
- Possibly conflicting demands on onboard sensors
  (Support flight operations or ground navigation?)



Specifying behavior with temporal logic

Linear Temporal Logic (LTL) = **Propositional Logic** + **Temporal Operators**

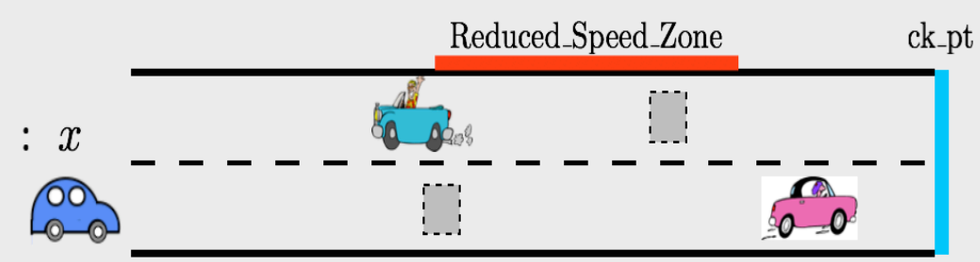
$\wedge$ (and)
$\vee$ (or)
$\rightarrow$ (implies)
$\neg$ (not)

$\Diamond$ (eventually)
$\Box$ (always)
$\mathcal{U}$ (until)

- Reason about infinite sequences $\sigma = s_0 s_1 s_2 \ldots$ of states
- Many different dialects of temporal logic (with probabilistic and epistemic modalities)
- Specify safe, allowable, required, or desired behavior of system and/or environment.

Traffic rules:

- No collision $\Box\,(\mathrm{dist}(x, \mathrm{Obs}) \geq X_{\mathrm{safe}} \wedge \mathrm{dist}(x, \mathrm{Loc}(\mathrm{Veh})) \geq X_{\mathrm{safe}})$
- Obey speed limits $\Box\,((x \in \mathrm{Reduced\_Speed\_Zone}) \rightarrow (v \leq v_{\mathrm{reduced}}))$
- Stay in travel lane unless blocked
- Intersection precedence & merging, stop line, passing,...



Goals:

- Eventually visit the check point $\Diamond(x = \mathrm{ck\_pt})$
- Every time check point is reached, eventually come to start

$$\Box((x = \mathrm{ck\_pt}) \rightarrow \Diamond(x = \mathrm{start}))$$

Environment assumptions:

- Each intersection is clear infinitely often $\Box\Diamond(\mathrm{Intersection} = \mathrm{empty})$
- Limited sensing range, detect obstacles before too late,...

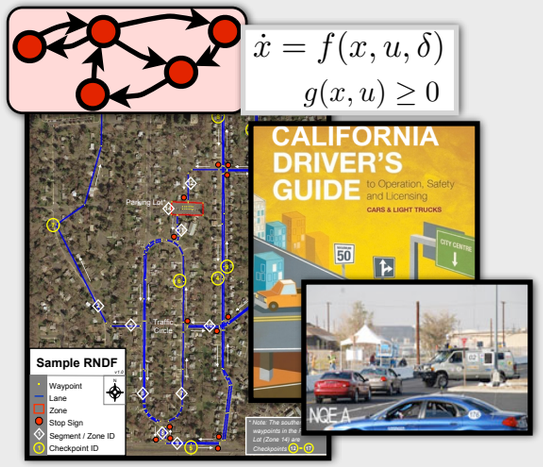
Protocol Synthesis Problem

[adapted to an autonomous navigation scenario]

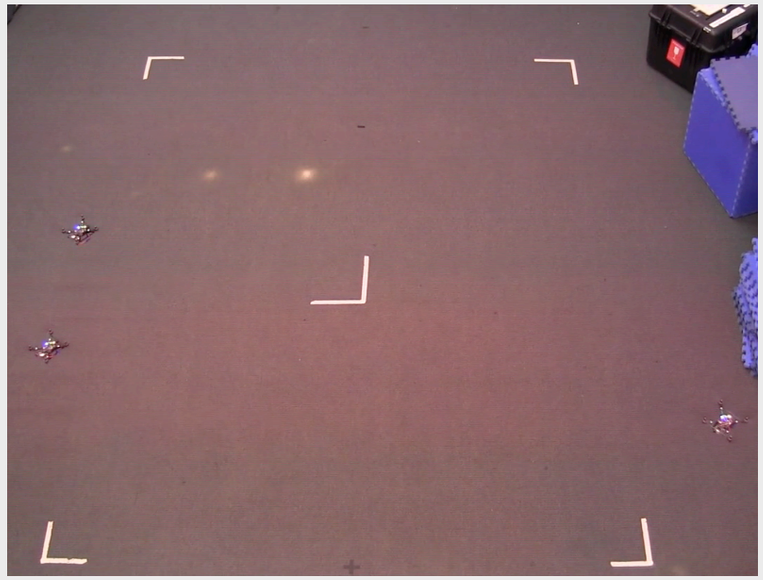
Given:

- *System model*
  - both continuous & discrete evolution
  - actuation limitations
  - modeling uncertainties & disturbances
- *Specifications*
  - high-level requirements & goals
  - knowledge about the a priori unknown, dynamic environment

$$(\varphi_{\text{init}} \wedge \varphi_{\text{env}}) \rightarrow (\varphi_{\text{safety}} \wedge \varphi_{\text{goal}})$$



two uncontrolled robots +
one controlled robot

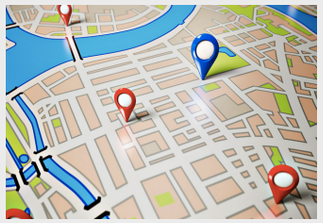
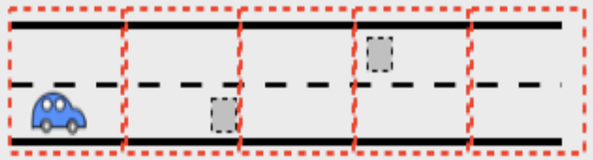
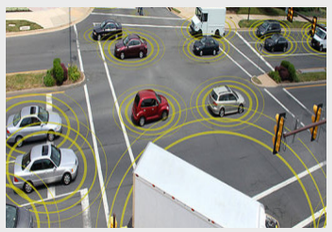
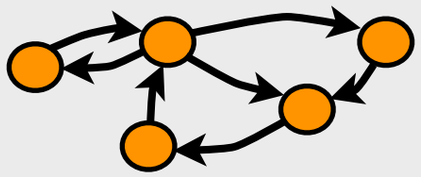
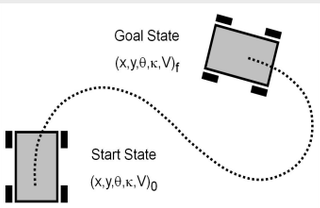
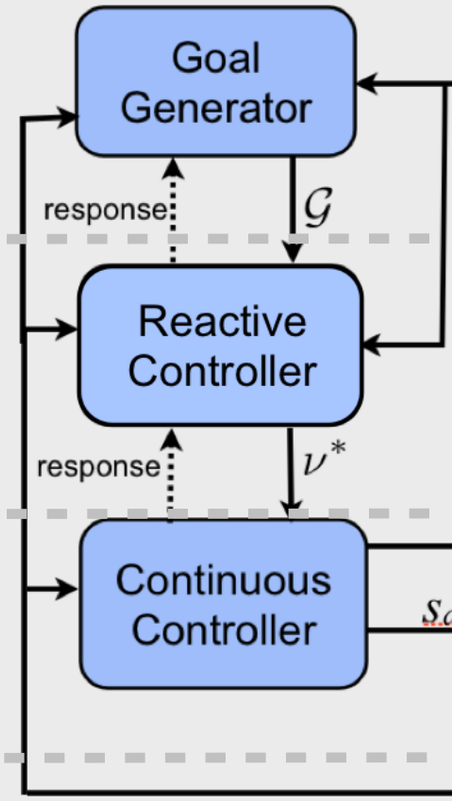


Min Wen in collaboration with Kumar Lab at Penn

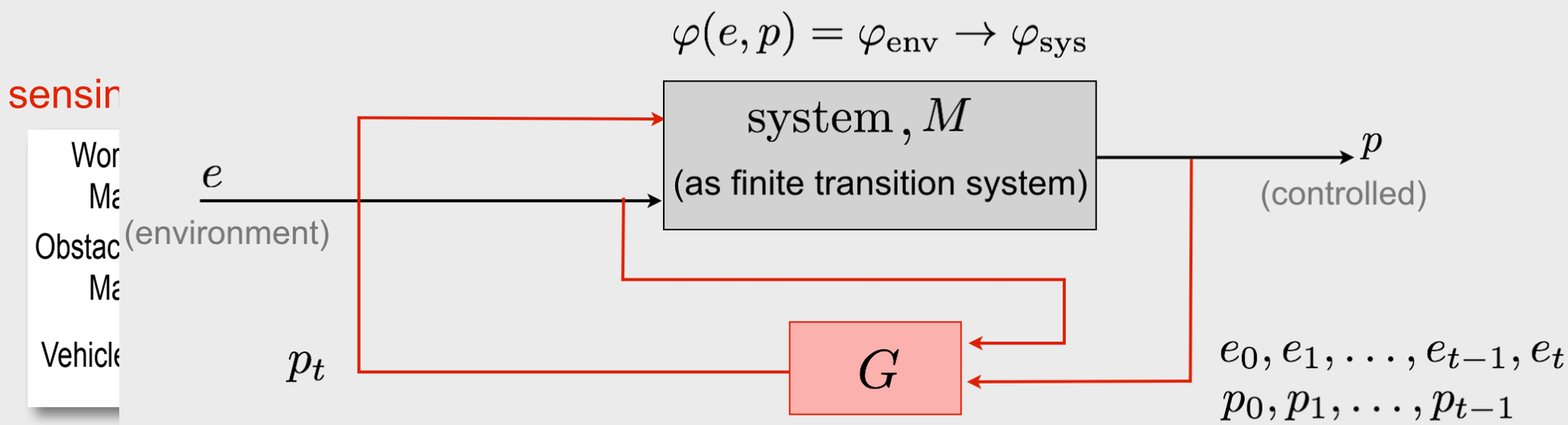
Automatically synthesize a control protocol that

- manages the system behavior;
- reacts to changes in external environment
- is provably correct w.r.t. specifications.

A Solution: Hierarchical Control Structure

Different views	Multi-scale models	Synthesis method	Control protocol
 long-horizon specifications		Iterative graph search	
 short-horizon specifications		Two-player, turn-based graph game	
 constraints on continuous state + input	$x_{t+1} = f(x_t, w_t, u_t)$ $x \in \mathcal{X}, u \in \mathcal{U}, w \in \mathcal{W}$	Constrained, finite-horizon optimal control	

Reactive Synthesis as Two-Player Temporal Logic Game



Focus of the project: Sensing and perception limitations introduce partialness in information

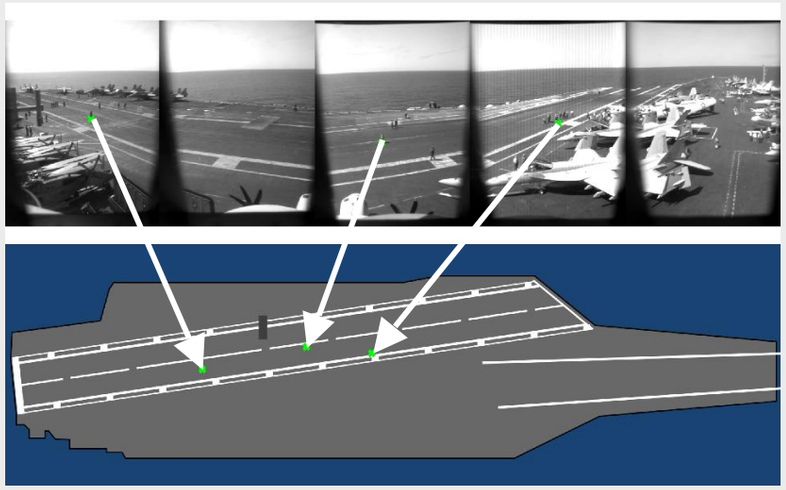
Outline

- An example source of information — vision-based perception
- Sensor design for reactive synthesis
- Sensor design in POMDPs
- Active sensing
- Hierarchical control in partial-observation stochastic games

Vision-based perception: Build a semantic map of deck from image

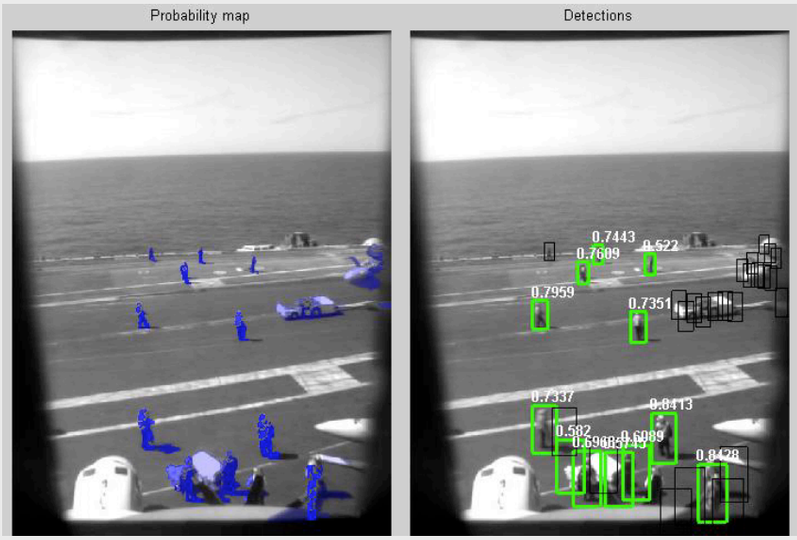
Homography estimation

Relate the points from image to deck



Object detection

Find the locations in the image



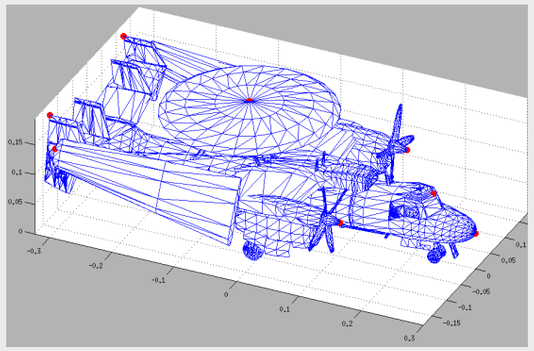
- Generate proposals by background subtraction
- Classify each proposal as object or not by a learned classifier
- The score output by the classifier gives a measure of uncertainty

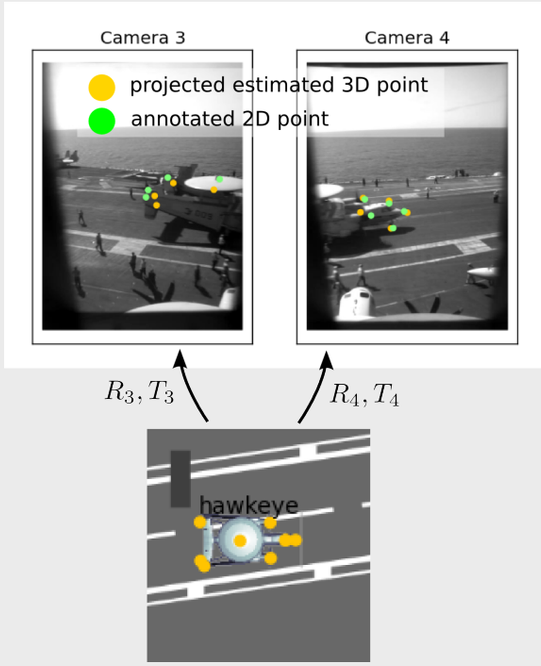
Output: object class and confidence

Object pose estimation

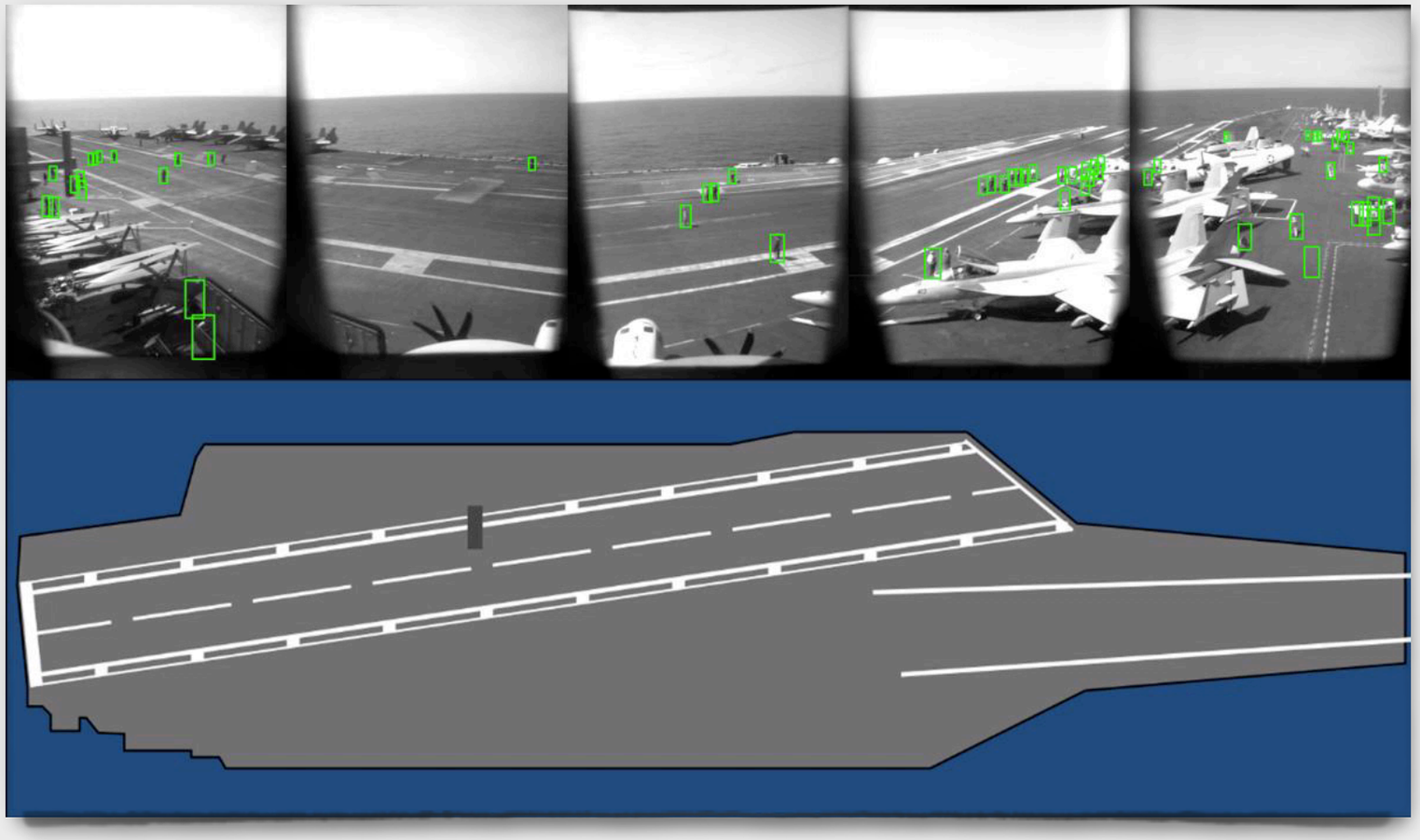
Estimate rotation and translation in the 3D space, i.e., the deck

- Define keypoints on the 3D model
- Detect keypoints in the 2D image
- Estimate the 3D pose parameters from the 3D-to-2D-keypoint correspondences

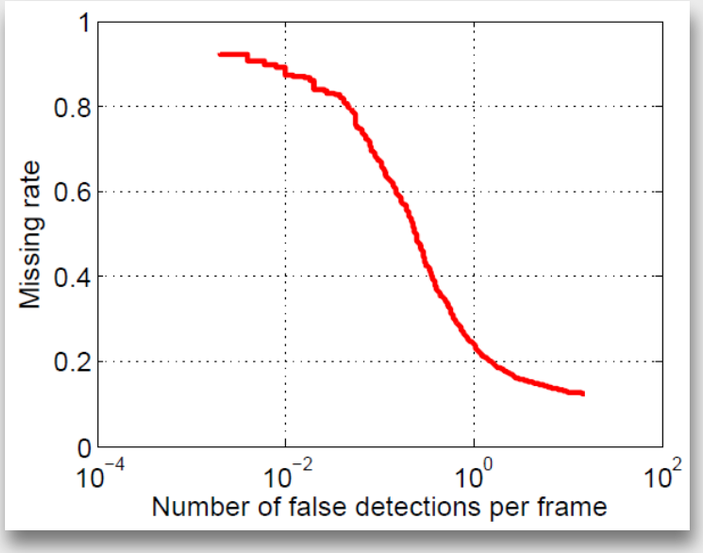


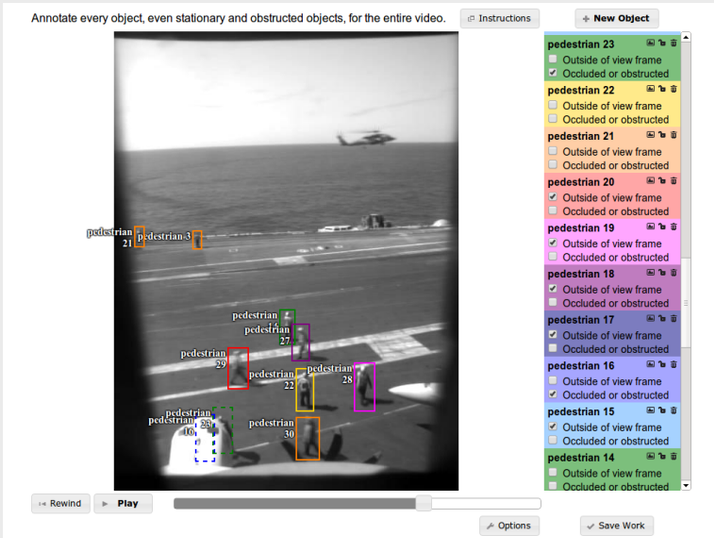


Vision-based perception: Build a semantic map of deck from image



Quantitative evaluation for pedestrian detection





Annotate objects

Annotate keypoints

Ground truth manually annotated by humans

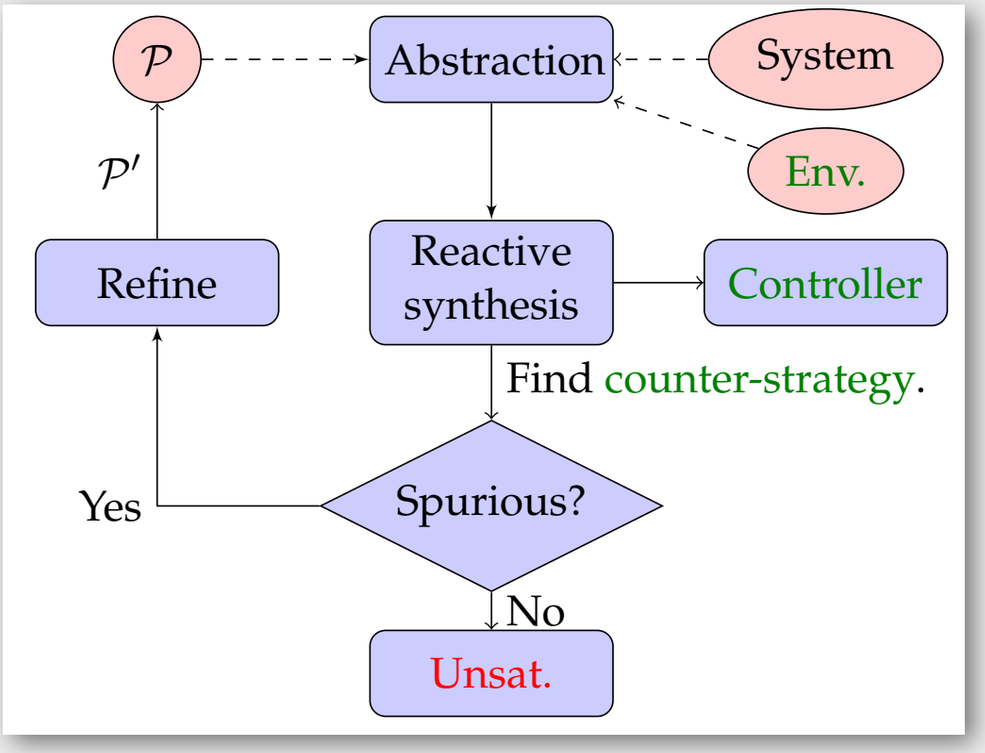
Sensor Design for Reactive Protocol Synthesis

Two-player, temporal-logic game with partial information

Given: A system with possibly infinite state space and a partially observed, dynamic environment and a safety specification.

Goal:

- Construct a reactive strategy that realizes the specification.
- If the specification is not realizable, design new sensors (their precision + temporal availability) that, when included, lead to a feasible synthesis problem.

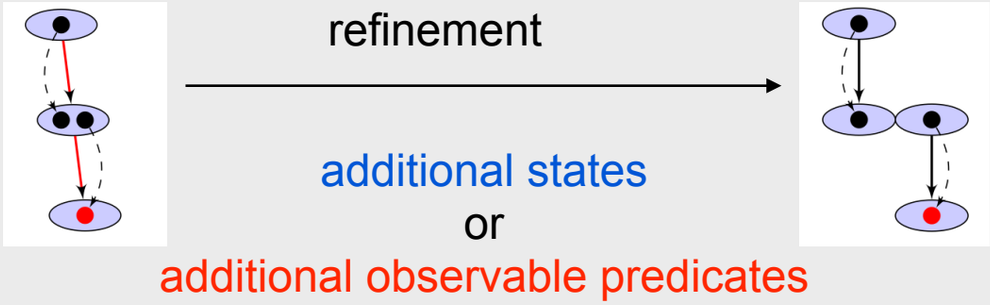


If **not realizable**, then **EITHER**

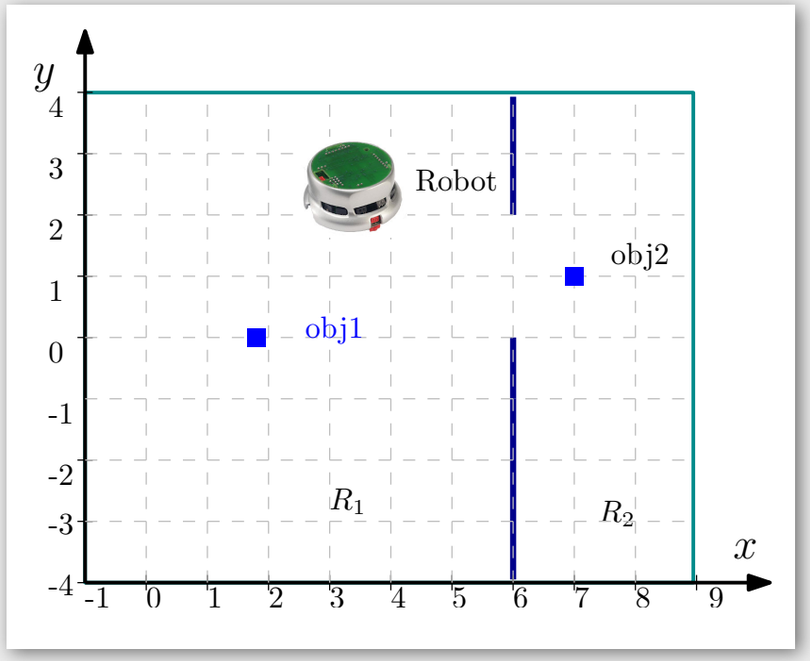
- the specification is unrealizable

OR

- the **abstraction** is too coarse **and/or**
- the **sensor model** is too coarse.



Case Studies



Problem setting:

- The behavior of (uncontrolled) obj2 not known a priori but is known to satisfy certain temporal logic specification
- obj1 is to eventually reach R2 while avoiding crash with obj2 and the walls

(1) Intermittent information:

- Value of y is known only every other step
- Maintain upper and lower bounds on y (when it is not known)

- Winning strategy after 17 iteration, 45 predicates
- Sensors that measure with one decimal precision suffice
- No need to keep track of upper bound on obj1's y-position or the y-position of obj2

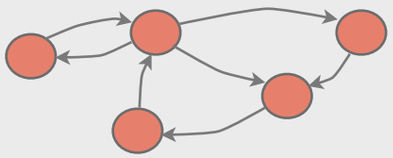
(2) Local sensing:

- Cannot observe obj2 while in R1 and obj1 while in R2
- Winning strategy after 21 iterations and 60 predicates

Sensor Design in Partially Observable Markov Decision Processes

Given:

- A partially observable Markov decision process (POMDP) with partially defined observation function
- A reachability objective



- Probabilistic transitions
- In a subset of the states, a subset of the observations is available

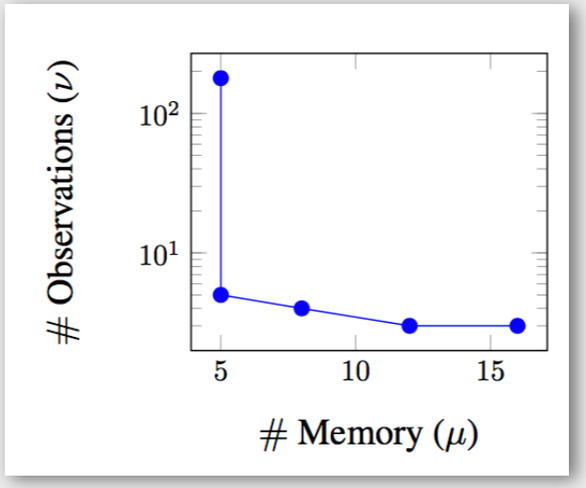
Problem: Does there exists…

- … a completion (of the observation function) not using more than n additional observations…
- … such that, in the resulting POMDP, there exists an almost sure winning policy not using more than m memory elements?

Sample results:

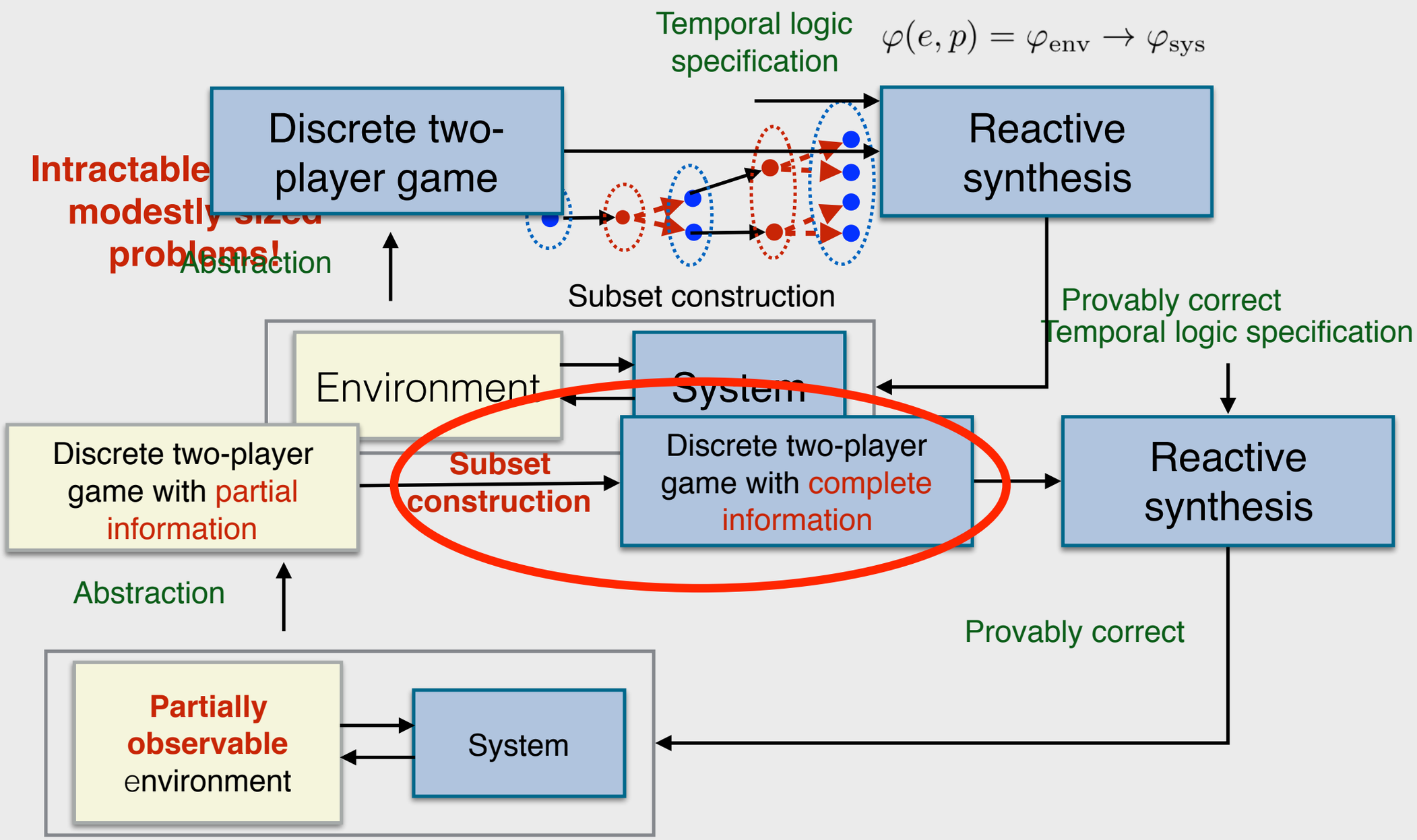
- The problem is NP-complete.
- Developed an algorithm based on SAT solving (for which highly scalable heuristics exist).
- Applied to wide range of problems in literature.
- Demonstrated tradeoffs between amount of observations and necessary memory.

Order of magnitude reduction in sensing is possible with small increase in memory (i.e., complexity).



Active Sensing — Motivation

Bottleneck in partial-info synthesis: Complexity growth due to ambiguity that needs to be accounted for.



Active Sensing — **Approach**

Interleave between:	offline, complete-information planning for progress	+	online, randomized strategy for information/ sensing

(pro)actively initiate *sensing queries* to reduce the ambiguity in the belief

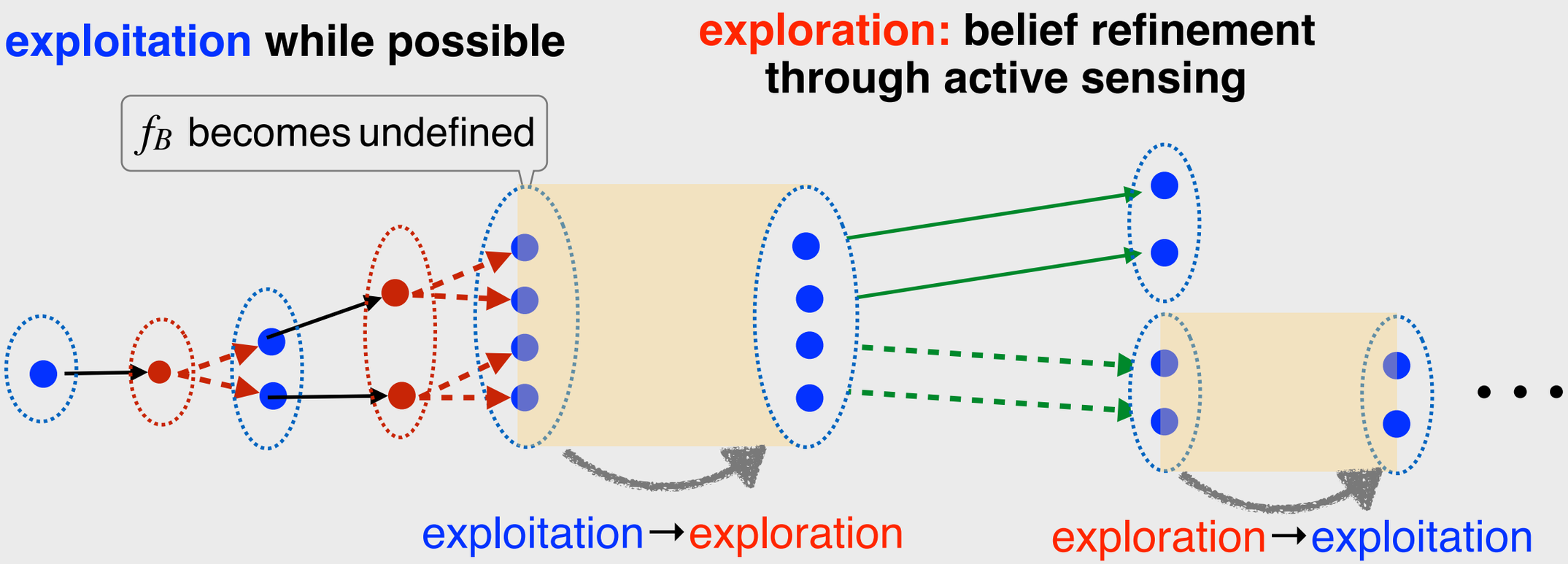
Introduce active sensing into reactive synthesis under temporal logic constraints in dynamic, uncontrollable environment.

Avoid the computational complexity in off-line solutions for games with partial information.

Provable correctness guarantee under the assumption that there are *no belief dead-ends*.

Use the active sensing “minimally”.

Active Sensing — Main result: Exploitation ⇌ Exploration



Theorem: If there are no belief dead-ends, then the switching strategy ensures almost-sure satisfaction of the specification.

generally a limitation in online planning

provably correct BUT in a different sense

Where is the gain then? No subset construction!

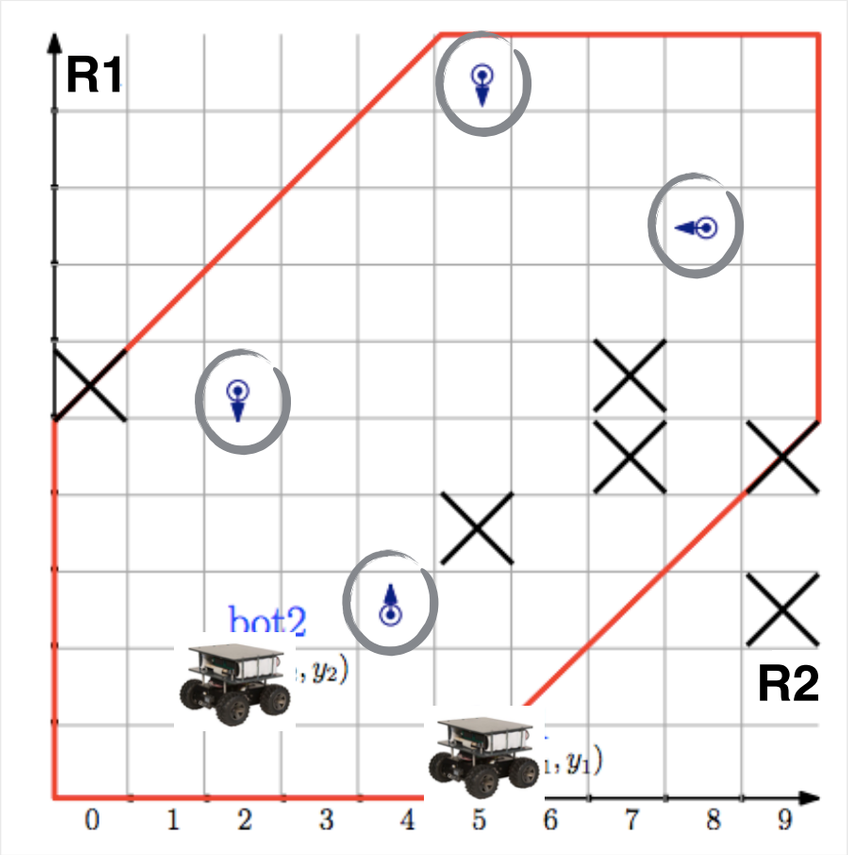
Active Sensing — Example

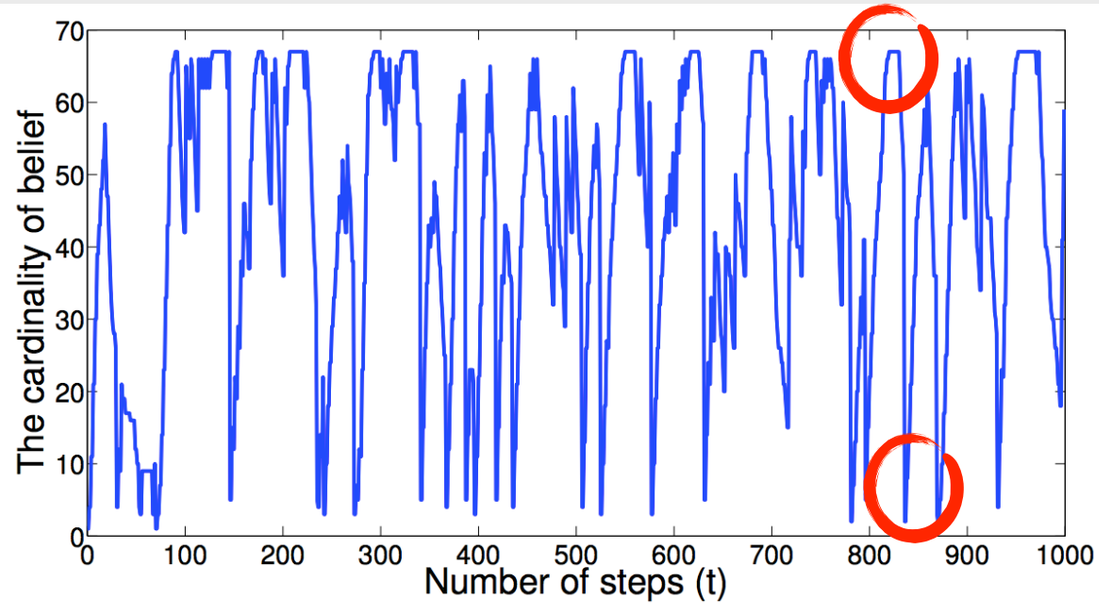
Distributed sensors

Bot1: Controlled
Bot2: Uncontrolled

Sensor: Detect whether there is a robot in its range.

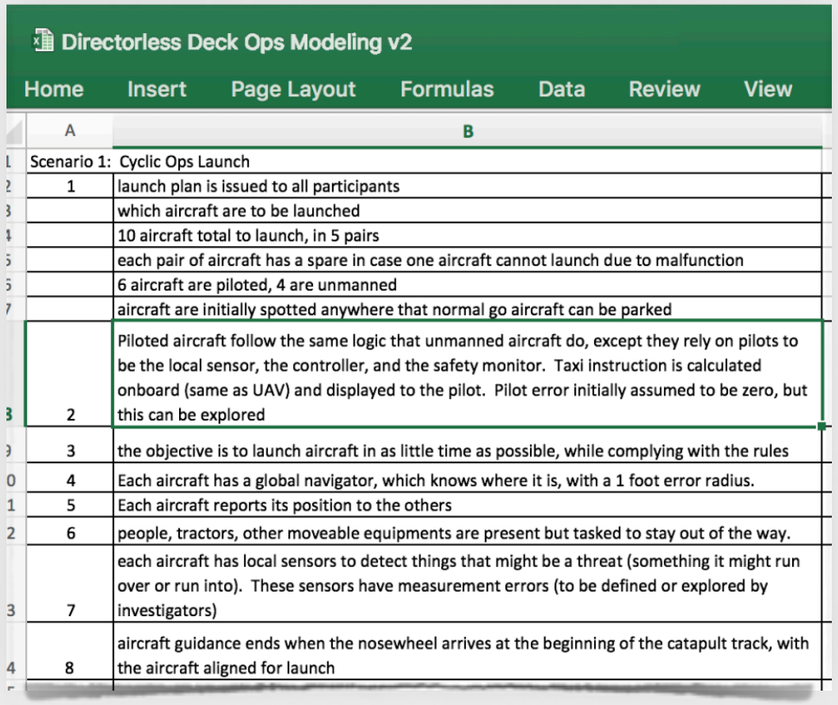
Specification: Always eventually visit R1 and R2, and avoid unsafe region and bot2.





Num. of sensors	Comp. time	Revisits	Num. of sensing acts
10	551	11	423
8	540.16	10	421
6	525.61	11	403

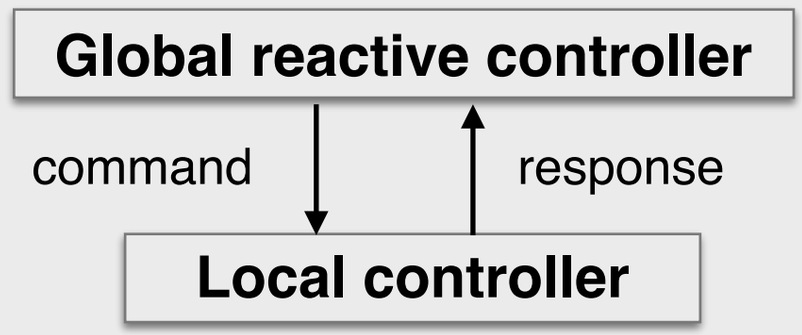
Hierarchical Control in Partial-Observation Stochastic Games



Directorless Deck Ops Modeling v2

Home Insert Page Layout Formulas Data Review View

	A	B
1	Scenario 1:	Cyclic Ops Launch
2	1	launch plan is issued to all participants
3		which aircraft are to be launched
4		10 aircraft total to launch, in 5 pairs
5		each pair of aircraft has a spare in case one aircraft cannot launch due to malfunction
6		6 aircraft are piloted, 4 are unmanned
7		aircraft are initially spotted anywhere that normal go aircraft can be parked
8	2	Piloted aircraft follow the same logic that unmanned aircraft do, except they rely on pilots to be the local sensor, the controller, and the safety monitor. Taxi instruction is calculated onboard (same as UAV) and displayed to the pilot. Pilot error initially assumed to be zero, but this can be explored
9	3	the objective is to launch aircraft in as little time as possible, while complying with the rules
10	4	Each aircraft has a global navigator, which knows where it is, with a 1 foot error radius.
11	5	Each aircraft reports its position to the others
12	6	people, tractors, other moveable equipments are present but tasked to stay out of the way.
13	7	each aircraft has local sensors to detect things that might be a threat (something it might run over or run into). These sensors have measurement errors (to be defined or explored by investigators)
14	8	aircraft guidance ends when the nosewheel arrives at the beginning of the catapult track, with the aircraft aligned for launch

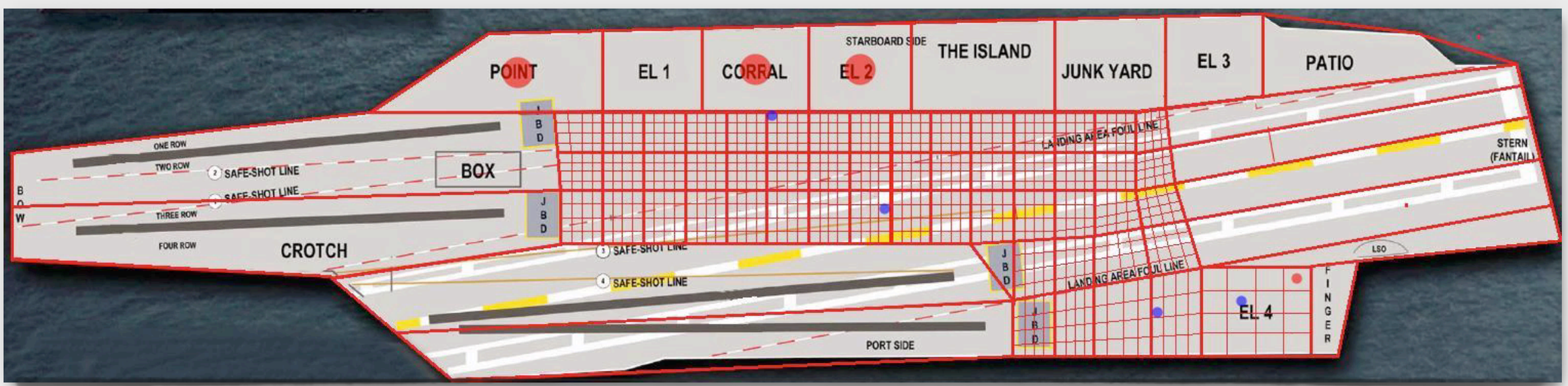


(use global navigator)

Perfect-information game

POMDP

(use the onboard sensors for the small objects and personnel in the vicinity)



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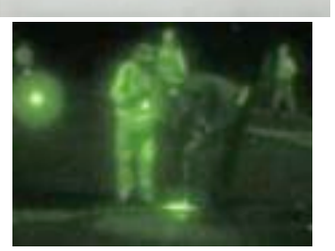

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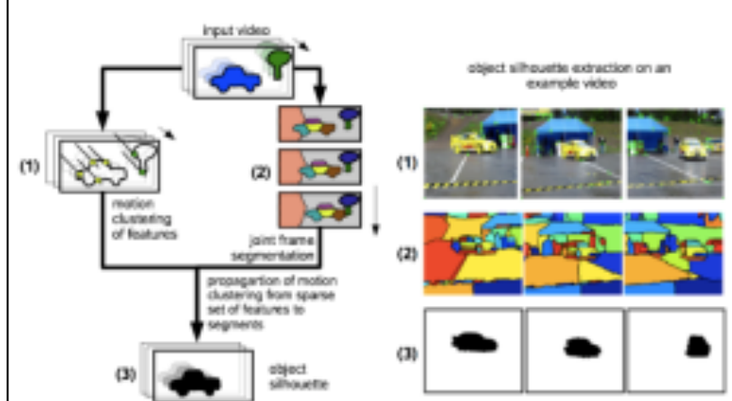
- Segmentation and semantic mapping of moving objects



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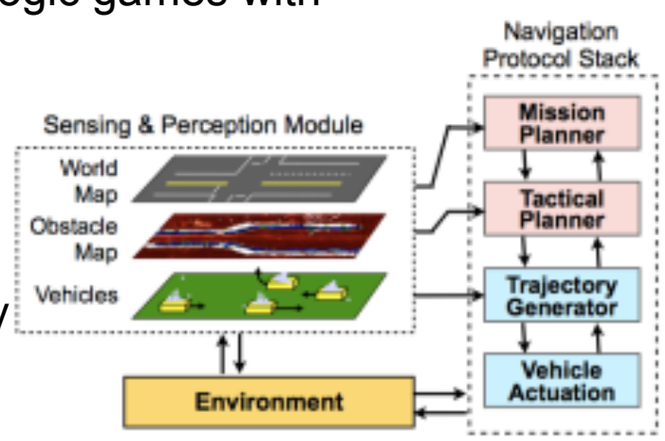

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FY 15	•Temporal persistence & dynamic objects in perception •Integrate probabilistic perception uncertainty into the protocols	
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