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

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**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 – 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.

**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.

**Schedule, evaluation & transition**:  
**FY 14**
- Perception for static objects
- Protocols for joint planning and information gathering

**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

Develop a case study with typical deck layout, operation scenarios, rules & constraints, sensing modalities & limitations. Update each year to align with research.
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

\[ \land \quad \lor \quad \rightarrow \quad \neg \quad (\text{and}) \quad (\text{or}) \quad (\text{implies}) \quad (\text{not}) \]

\[ U \quad (\text{until}) \]

- 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 \( \square (\text{dist}(x, \text{Obs}) \geq X_{\text{safe}} \land \text{dist}(x, \text{Loc(Veh)}) \geq X_{\text{safe}}) \)
- Obey speed limits \( \square ((x \in \text{Reduced.Speed.Zone}) \rightarrow (v \leq v_{\text{reduced}})) \)
- Stay in travel lane unless blocked
- Intersection precedence & merging, stop line, passing,....

Goals:
- Eventually visit the check point \( \Diamond (x = \text{ck.pt}) \)
- Every time check point is reached, eventually come to start
  \[ \square ((x = \text{ck.pt}) \rightarrow \Diamond (x = \text{start})) \]

Environment assumptions:
- Each intersection is clear infinitely often \( \square \Diamond (\text{Intersection} = \text{empty}) \)
- 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

\[(\varphi_{\text{init}} \land \varphi_{\text{env}}) \rightarrow (\varphi_{\text{safety}} \land \varphi_{\text{goal}})\]

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

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<td>$x_{t+1} = f(x_t, w_t, u_t)$ $x \in \mathcal{X}, u \in \mathcal{U}, w \in \mathcal{W}$</td>
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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

Ground truth manually annotated by humans

Annotate objects

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

- refinement
- additional states or
- additional observable predicates
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

**Problem:** Does there exist...
- ...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).
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: \textbf{Exploitation} $\nRightarrow$ \textbf{Exploration}

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

\textbf{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.
Hierarchical Control in Partial-Observation Stochastic Games

Global reactive controller

command

response

Local controller

Perfect-information game

POMDP

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

(use global navigator)
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