ARETHUS – A Decision Support Platform for Port Security

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http://agents.cz

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Agent Technology Center

Part of Faculty of Electrical Engineering, Czech Technical University in Prague

Led by prof. Michal Pechoucek

10-year history

35 full-time researchers and PhD students

20+ research projects

fundamental and applied research in autonomous agents and multi-agent systems
ATG Expertise

- Autonomous agents and multi-agent systems
- Behaviour modelling and analysis
- UAS
- Multi-agent planning
- Game theory

Agent-based simulation
Application Areas

Air Traffic Management
Critical Infrastructure Security
Network Security
Autonomous Aerial Vehicles
Intelligent Transport Systems
Logistics and Manufacturing
AgentFly Air Traffic Simulation
Arethusa Project

First phase

• Integration with CRA with emphasis on HMI
• Diverse planning
• Multiple waypoint planning
• Moving obstacles

Second phase

• Decision support system
• Mixed architecture concept
• Integration with hardware
• Rich scenario set
Second Phase
Decision Support System

Vision
Mixed-reality concept

Architecture

Modules
Decision Support System
Simulation
Visualization

Scenarios
Boston Harbor
Prague
Oil-pipe Patrolling
Decision Support System with Mixed-reality Architecture

(Truly) Modular - very loose coupling

Mixed-reality concept

Machine
- Simulated entities
- Hardware-in-the-loop
- Hybrid simulation
- Full Hardware

Human
- Computational Behavior Models
- Data Feeds about human behavior
- Virtual Reality
- Simulated Human-Machine interaction
- Full human involvement

Towards HW Deployment

( Mixed Reality Simulation )
Decision Support System

1. Design Control
   - Camera Placement
   - Default Strategies
   - Monitoring/Patrolling

2. Mission Control - OODA Loop
   - Processing of events

## Design Control – Camera Placement

<table>
<thead>
<tr>
<th>K-coverage of area</th>
<th>Cameras on buildings</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Realistic parameters (zoom, resolution)</td>
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<tr>
<td>Environ. repre.</td>
<td>Hexagonal grid</td>
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<table>
<thead>
<tr>
<th>Camera models</th>
<th>Cones</th>
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<tbody>
<tr>
<td></td>
<td>Min/Max distance</td>
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<table>
<thead>
<tr>
<th>Complexity</th>
<th>NP-hard problem – 6 DOF</th>
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<tr>
<td></td>
<td>Submodular problem</td>
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<tr>
<td></td>
<td>Greedy approximation</td>
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https://dl.dropboxusercontent.com/u/4546445/ARETHUS/cameras.mp4
Event Processing

Sensors generate data → events

events reported to the system

**events processed**

Results presented to the operator

... stored in the Knowledge-base

---

**Complex Event Processor**

Based on WSO2 CEP

Cassandra NoSQL DB

Siddhi SQL language

Knowledge mining from events
Simulation Framework

Simulation feeds in data not available from the real world

Real time execution

Built on custom queue implementation

- Event-based agent behavior models

Data based on OpenStreetMaps

- PostGIS database
- Osm2pgsql importer
Agent Computational Behavior Models

Agents

- cars
- ships – schedules, AIS stations
- people – crowds – AgentCrowd project

Integration of crowd project

- Enables modeling of crowds and intentions
- Grey team and red team
- Not scalable to cities – proposal for enhancement
Visualization

Browser-based

Geospatial

• Google Earth does not support feedback

AGI Cesium

• WebGL 3D globe
• Javascript library

CZML language

• similar to KML, based on JSON
• supports streams and event-based updates
• supports dynamic data

jQuery

• user interface
Real-time image capturing

Real-time video embedded

Image collection
- Defined fps

Image localization and mapping
- Using GPS from autopilot
- Angle correction

Camera bank correction

Resolution
- 400 x 400
- 1920 x 1080 details
<table>
<thead>
<tr>
<th>Scenarios</th>
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<tr>
<td>Boston Harbor</td>
<td>physical security testbed</td>
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<tr>
<td>Prague</td>
<td>mixed-reality testbed</td>
</tr>
<tr>
<td>Pipeline protection</td>
<td><strong>Critical infrastructure protection</strong></td>
</tr>
<tr>
<td></td>
<td>testbed</td>
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</tbody>
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From 2013 reported 3176 oil spills. Largest ones in hundreds thousands of liters (thousands of barrels) - aging facilities, human error.
Problem Overview

How to allocate UAV bases and how to plan UAV trajectories to discover leaks ASAP?

- Base allocation
- UAV assignment
- Trajectory planning with constraints on speed and endurance

No adversarial actions (yet)
## Related Work

<table>
<thead>
<tr>
<th>Authors</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dawolota et al. [2010]</td>
<td>Set of <strong>decision methods for risk management</strong> of oil and gas pipelines.</td>
</tr>
<tr>
<td>Dey et al. [2004]</td>
<td><strong>Risk-based decision support system</strong> that reduces the amount time spent on Inspection.</td>
</tr>
<tr>
<td>Tapanes [2001]</td>
<td>Real-time <strong>pipeline integrity monitoring</strong> using Fiber Optic Technology.</td>
</tr>
<tr>
<td>Nigam and Kroo [2008]</td>
<td>Problem of <strong>persistent surveillance</strong> with a focus on creating a <strong>trajectory for UAVs</strong> with respect to aircraft dynamics.</td>
</tr>
<tr>
<td>Jakob et al. [2010]</td>
<td>Problem of coordination and planning for <strong>aerial single-area surveillance</strong>.</td>
</tr>
<tr>
<td>Pasqualetti et al. [2012]</td>
<td>Problem of <strong>cooperative patrolling</strong> using graph theory.</td>
</tr>
<tr>
<td>Chevaleyre [2004]</td>
<td><strong>Patrolling problem on a graph</strong> as a computation of trajectory minimizing time lag between two visits in each node.</td>
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</table>
Environment Representation

Graph-like structure of oil pipe system

Discretized pipeline graph or Hexagonal grid (triangular graph)

We allow differing lengths of edges, however, the edge has to be traversed in an integer number of steps – spatio-temporal discretization w.r.t. UAV (differing) speeds.

Base allocation

- Base(s) placed in the graph – starting and ending positions of UAVs
- Each UAV assigned to a base permanently – UAV home base
Agent Movement

Agents **starting** and **recharging** at their home **bases**

Agents have **differing speeds**

Agents have a **limited endurance** expressed by **available flight time** of agent k in time t

**Collision avoidance** (optional)

at most one agent on edge e in time t

Loosing many high-quality solutions – collision avoidance solved during execution
Definition of Solution Cost

Environment Sensitivity Index (ESI) - values from 1-10

Age of Information – time of damage not detected

Solution Approach - MILP

\[
\begin{align*}
\min \sum_{t \in T} \sum_{e \in E} c_e^t \\
c_e^0 &= 0 \\
\forall e &\in E \\
c_e^t &\geq c_e^{t-1} + C_e \cdot \tau - M \cdot \gamma_e^t \\
\forall e &\in E, \forall t \in [1, T] \\
\gamma_e^t &\leq \sum_{k \in K} \sum_{i=0}^{\sigma_e^{k-1}} \left( k \cdot a_e^{t-i} + k \cdot a_{\bar{e}}^{t-i} \right) \\
\forall e &\in E, \forall t \in [1, T] \\
\sum_{e \in out(n)} k \cdot a_e^{t-\sigma_e^k} &= k \cdot b_n \\
\forall k &\in K, \forall n \in N \\
\sum_{e \in in(n)} k \cdot a_e^{T-\sigma_e^k} &= k \cdot b_n \\
\forall k &\in K, \forall n \in N \\
k \cdot d_t^t &\leq k \cdot d_t^{t-1} - \tau + (k \cdot R + \tau) \cdot k \cdot a_{\lambda(n)}^t \cdot k \cdot b_n \\
\forall t &\in [1, T], \forall k \in K, \forall n \in B \\
m_n &\geq \frac{1}{|K|} \cdot \sum_{k \in K} k \cdot b_n \\
\forall n &\in B \\
\sum_{n \in N} m_n &\leq \beta
\end{align*}
\]
Complete Model

Minimize the cost of solution.

It is zero at the beginning...

... and grows in time if edges are not covered...

\[ \gamma_e^t \leq \sum_{e \in E} \sum_{t \in T} \left( k a_e^{t-i} + k a_e^{t-i} \right) \]

... as defined above.

\[
\sum_{e \in E} k a_e^t \leq k a_{\lambda(n)}^{t-1} + \sum_{e \in \lambda(n)} \sum_{e \in \lambda(n)} k a_e^{t} \max\{t-\sigma_e^k: 0\} \]

\[ \forall k \in K, \forall n \in N, \forall t \in [1, T] \]

\[ \sum_{e \in E} k a_e^t \leq 1 \]

\[ \forall k \in K, \forall t \in T \]

\[
\sum_{e \in E} k a_e^0 = 0 \quad \forall k \in K
\]

\[
\sum_{e \in \text{out}(n)} k a_e^1 = k b_n \quad \forall k \in K, \forall n \in N
\]

\[
\sum_{e \in \text{in}(n)} k a_e^{T-\sigma_e^k} = k b_n \quad \forall k \in K, \forall n \in N
\]

\[
k a_e^t \leq k a_{\lambda(n)}^{t-1} - \tau + (k R + \tau) \cdot k a_{\lambda(n)}^t \cdot k b_n \quad \forall t \in [1, T], \forall k \in K, \forall n \in B
\]

\[
m_n \geq \frac{1}{|K|} \cdot \sum_{k \in K} k b_t \quad \forall n \in B
\]

\[
\sum_{n \in N} m_n \leq \beta
\]
Complete Model

Minimize the cost of solution.

It is zero at the beginning...

... and grows in time if edges are not covered...

\[ \gamma_e^t \leq \sum_{i} \sum_{e \in E} \left( k^a_{e-i} + k^a_{e-i} \right) \]

... as defined above.

Agents' trajectories are valid paths...

\[ \sum_{e \in E} k^a_e \leq 1 \]

\[ m_n \geq \frac{1}{|K|} \cdot \sum_{k \in K} k b_n \]

\[ \sum_{n \in N} m_n \leq \beta \]
Complete Model

Minimize the cost of solution.

It is zero at the beginning...

... and grows in time if edges are not covered...

\[ c_e^t = c_e^{t-1} + C_{\gamma_e} T - M_{\gamma_e}^t \]

\[ \forall e \in E, \forall t \in [1, T] \]

... as defined above.

\[ \gamma^t_e \leq \sum_{i=1}^{\sigma_e^t} \left( k a_{e,i}^{t-i} + k a_{e,i-1}^{t-i} \right) \]

\[ \forall e \in E, \forall t \in [1, T] \]

\[ \sum_{e \in \text{out}(n)} k a_{e}^{t} \leq k a_{\lambda(n)}^{t-1} + \sum_{e \in \text{in}(n)} k a_{e}^{\max\{t-\sigma_e^k; 0\}} \]

\[ \forall k \in K, \forall n \in N, \forall t \leq \lambda(n) \]

\[ \sum_{e \in E} k a_{e}^{t} \leq 1 \]

\[ \forall k \in K, \forall t \in T \]

Agents' trajectories are valid paths...

... starting in their base...

\[ \sum_{e \in \text{out}(n)} k a_{e}^{1} = k b_n \]

\[ \forall k \in K, \forall n \in N \]

... and ending in their base.

\[ \sum_{e \in \text{in}(n)} k a_{e}^{T-\sigma_e^k} = k b_n \]

\[ \forall k \in K, \forall n \in N \]

The agents have to recharge periodically.

\[ m_n \geq \frac{1}{|K|} \sum_{k \in K} k b_k \]

\[ \forall n \in B \]

\[ \sum_{n \in N} m_n \leq \beta \]
Complete Model

Minimize the cost of solution.

It is zero at the beginning...

... and grows in time if edges are not covered...

\[ c_e^t \geq c_e^{t-1} + C_{e} \left( 1 - M_{e} \right)^{\gamma_e^t} \]

... as defined above.

\[ \forall e \in E, \forall t \in [1, T] \]

\[ \gamma_e^t \leq \sum_{i=1}^{k} \left( k a_e^{t-i} + k a_e^{t-i} \right) \]

... starting in their base...

\[ \forall k \in K \]

... and ending in their base.

\[ \forall k \in K, \forall n \in N \]

The agents have to recharge periodically.

\[ k a_e^{t-\sigma_e^k} = k b_n \]

\[ \forall k \in K, \forall n \in N \]

The assignment of agents into bases is static...

\[ \sum_{e \in E} k a_e^t \leq 1 \]

\[ \forall k \in K, \forall n \in N, \forall t \in [1, T] \]

\[ \sum_{e \in E} k a_e^t \leq 1 \]

\[ \forall k \in K, \forall t \in T \]

... and there are at most B bases in the graph.
Complete problem

\[ CM(G, \beta, K, T, D, R, \sigma, *B, *^k B, *S) \rightarrow B, ^k B, S \]

\[ BAP(G, \beta, D, \sigma) \xrightarrow{B} CM(G, \beta = |B|, K, T, D, R, \sigma, B) \rightarrow S \]

\[ BAP(G, \beta, D, \sigma) \xrightarrow{B} ICM(G, \beta = |B|, K, T, D, R, \sigma, B) \rightarrow S \]

\[ BAP(G, \beta, D, \sigma) \xrightarrow{B} ICM(G, \beta = |B|, K, D, R, \sigma, B) \xrightarrow{^kB} TPP(G, K, T, D, R, \sigma, ^k B) \rightarrow S \]
Scalable Algorithms - Decompositions

Complete problem

$CM(G, \beta, K, T, D, R, \sigma, B^*, B^k, S) \rightarrow B^k, B, S$

Base allocation

$BAP(G, \beta, D, \sigma) \xrightarrow{B} CM(G, \beta = |B|, K, T, D, R, \sigma, B) \rightarrow S$

Agent assignment + Trajectories

$BAP(G, \beta, D, \sigma) \xrightarrow{B} ICM(G, \beta = |B|, K, T, D, R, \sigma, B) \rightarrow S$

$BAP(G, \beta, D, \sigma) \xrightarrow{B} ICM(G, \beta = |B|, K, D, R, \sigma, B) \xrightarrow{kB} TPP(G, K, T, D, R, \sigma, B^k) \rightarrow S$

Agent assignment $\rightarrow$ Agent trajectories
1. Base allocation problem

\[ BAP(G, \beta, D, \sigma) \rightarrow B. \]

2. Iterative agent assignment & trajectory computation

\[ ICM(G, \beta = |B|, K, T, D, R, \sigma, B) \rightarrow ^kB, S \]

Base allocation

3. Trajectory computation

\[ TPP(G, K, T, D, R, \sigma, B, kB) \rightarrow S \]

Base allocation + agent assignment
Evaluation – Summary

Synthetic graphs, synthetic costs (normal dist.)
- CM not scalable, optimal solution only on small instances
- Provides quality bounds

Decompositions better scalability
- Lower quality
- BT comparable quality

Correlation of scalability with quality
Evaluation – Rostock Harbor

30 km of pipelines – 8 km² → graph with 483 nodes and 1427 edges

5 UAVs, 30 min endurance, speed 50 km/h

Using BTi alg → 764 min → coverage of 90.7% of edges
Future

Platform is built with integration of external modules in mind

- Integration of TAF project cluster, AgentCrowd project
- Integration of other projects

Heavily utilizes OpenStreetMaps

Heavily utilizes AGI Cesium

- Still bleeding-edge
- Great potential

How to continue?

- Homeland security
- Border Patrol
- Critical Infrastructure protection

Thank you.

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