On-line Reasoning about Coordination Design Decisions

Frank Ehlers

2nd October 2015, DEMUR 2015
@IROS 2015, Hamburg
Outline

1. General Problem Description: Linking MoPs and MoEs

2. Decision Making on Coordination Design

3. Examples: a) Real application: multistatic sonar
   b) Mathematical treatment: game ‘fish vs. whales’

4. Reasoning as a Stochastic Game Played at Meta-Level

5. Efficient Independent Verification and Validation
   added as Lagrange constraint

6. Trading Independence against Efficiency

7. Summary and Applicability to General Problem
## MoPs and MoEs

<table>
<thead>
<tr>
<th>DESIGN</th>
<th>EXECUTION</th>
<th>EFFECTIVENESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor &amp; Platform &amp; Network</td>
<td>Operational &amp; Environmental</td>
<td>Military Objective &amp; Mission Goal</td>
</tr>
<tr>
<td>MoP Sensors</td>
<td>MoP Platforms</td>
<td>System MoE for a given</td>
</tr>
<tr>
<td>MoP Platforms</td>
<td>Operationally Expected Target Behavior</td>
<td>Concept of Operations</td>
</tr>
<tr>
<td>MoP Network</td>
<td>Environmental Conditions</td>
<td></td>
</tr>
</tbody>
</table>

- System MoP for a given Concept of Operations
- Connection of MoPs and MoEs without execution or sophisticated simulation
MoE: Measure designed to correspond to accomplishment of mission objectives and achievement of desired results.

MoP: Measure of a system’s performance expressed as distinctly quantifiable performance features.

MoS: Measure of Suitability, Measure of an item’s ability to be supported in its intended operational environment.

• The challenge in multi-robot coordination design is the mapping from implementation details (and Measures of Performance) to specifications while reasoning about how to achieve the operational goal (and Measures of Effectiveness).

• It is preferable to prepare an “EASY” methodology to approach this challenge, because in real applications multi-robot coordination is a complex task (see next slide).
WTD 71  Overarching Concept for Decision Making

Performance  ||  Effectiveness  ||  Efficiency

Reasoner Module decides on activation

Estimator  →  Reward Function  →  POSTERIORI

Controller

Design & Specification Optimization

Work on effectiveness conservation

Enhanced with “understanding”

Automatically and carefully constructed approximations

Real data from dedicated tests or execution of other Coordination Schemes
Examples (Start)

- Multistatic Sonar

- Fish and Whales


Clutter and target behavior realistically modelled

Initial guess towards building a solution: Target-clutter discrimination best if a patch is hit simultaneously by all three sound sources.
Coordination via sources: without further communication both AUVs focus on the same patch.

In the search phase: The patch is chosen randomly, jumping over the surveillance area, not giving the target a clue where to hide.
Optimization of target behavior: Hide at clutter points

For the surveillance it is not possible to know in which “Mental State” the target is, but the surveillance is able to geometrically take away degrees of freedom from the target.

→ Idea for coordination design for the surveillance: Minimization of relevant hidden information
The red arrows indicate a shrinking size of the surveillance area, due to suddenly occurring rain.

The effectiveness of the search in the remaining part of the surveillance area has to be increased.

- E.g. the deployment has to be changed.
Fish and Whales

<table>
<thead>
<tr>
<th>Game Setup</th>
<th>Execution</th>
<th>Winner (in terms of energy)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Game Setup Image 1" /></td>
<td><img src="image2.png" alt="Execution Image 1" /></td>
<td><img src="image3.png" alt="Winner Image 1" /></td>
</tr>
<tr>
<td><img src="image4.png" alt="Game Setup Image 2" /></td>
<td><img src="image5.png" alt="Execution Image 2" /></td>
<td><img src="image6.png" alt="Winner Image 2" /></td>
</tr>
<tr>
<td><img src="image7.png" alt="Game Setup Image 3" /></td>
<td><img src="image8.png" alt="Execution Image 3" /></td>
<td><img src="image9.png" alt="Winner Image 3" /></td>
</tr>
<tr>
<td><img src="image10.png" alt="Game Setup Image 4" /></td>
<td><img src="image11.png" alt="Execution Image 4" /></td>
<td><img src="image12.png" alt="Winner Image 4" /></td>
</tr>
<tr>
<td><img src="image13.png" alt="Game Setup Image 5" /></td>
<td><img src="image14.png" alt="Execution Image 5" /></td>
<td><img src="image15.png" alt="Winner Image 5" /></td>
</tr>
<tr>
<td><img src="image16.png" alt="Game Setup Image 6" /></td>
<td><img src="image17.png" alt="Execution Image 6" /></td>
<td><img src="image18.png" alt="Winner Image 6" /></td>
</tr>
</tbody>
</table>
Objective: START with 30 fish at the right, make sure 10 fish make it through.

Controlled movement of each individual fish in random media.
For a double slit experiment:

\[ dx(t) = u(x(t), t) dt + d\xi(t) \]

\[ C(x, t, u(\cdot)) = E_{path}(\int \left( \frac{1}{2} \right) R u^2(t) + V(x(t), t))) \]

\[ J(x, t) = \min_u C(x, t, u(t)) \]

→ Hamilton-Jacobi-Bellmann

\[ u = -\frac{1}{R} \partial_x J(x, t) \]

→ Cost-to-Go for small slit size

→ Multi-modal decision making
  at a critical time \( t_c \)

→ Binary channel for measurement uncertainty.

→ Analytic description of control & sensing
The challenge in multi-robot coordination design is the mapping from implementation details (state space equations) to specifications while reasoning about how to achieve the operational goal (reaching terminal condition).

Three coordination design solutions (initial guess):
- Individuals
- Hierarchy
- Swarm

Note: It is preferable to prepare an “EASY” methodology to approach this challenge, because in real applications multi-robot coordination is a complex task.
Coordination Design: Individuals

Controlled movement of each individual fish in random media.
Controlled movement of each individual fish in random media,

Added a "leader-follower coordination"
Coordination Design: Swarm

Neighborhood condition in the sense that each fish has to take on potential exit

time

2nd October 2015  On-line Reasoning about Coordination Design Decisions
If the whales do not know about the existence of 4th gap.
If whales do not eat the fish, the systems are decoupled.
Observations from Fish & Whales Example

- Four different types of “independence” extractable from the setup of the test bed:
  - Actual paths and decisions of fish as long as 1/3 get through
  - Final decision of each fish, depending on control noise before + hypothetically
  - Independence in terms of terminal condition possible
  - Independence of prior modelling: Deception

- Three different types of “irrelevance” for the evaluation of the coordination designs:
  - Individuals → state of other two fishes in the team
  - Hierarchy → decisions of two following fishes
  - Swarm → individual assignment to gap
Reachability aspect: changes are not always possible.

10 have to get through

3 at a time

30 fish

Time
Percolation aspect
Similarities to Multistatic Sonar

Optimization algorithm leads to maximized efficiency, e.g., lower number of participating units.

Reasoning leads to guaranteed effectiveness, e.g., number of escaped targets.

Details of system and coordination maintains independent activities of players within individual degrees of freedoms.

Optimized individual control and sensing:

\[
\begin{align*}
\dot{x}(t) &= f_x(x(t), u_x(t), y(t), u_y(t))dt + \sigma_x(x(t))d\omega_x(t) \\
y_x(t) &= h_x(x(t), u_x(t), y(t), u_y(t), \delta_x(t)) + N_xv_x(t)
\end{align*}
\]
Having a closer look at these similarities, there might be a chance to find a methodology behind this heuristic approach.

This methodology will be outlined in the following slides.
From the examples:

- (i) Minimization of relevant hidden information
- (ii) Independence
- (iii) Guaranteed reach of terminal condition
- (iv) Distributed decision making

→ Inserting Efficient independent Verification and Validation (EiV&V) as constraint into the Stochastic Differential Game.
Goal-driven. i.e. starting from Mission Goal

Real measurement data is necessary to ensure that the critical behavior is sufficiently well described for a follow-on extrapolation purpose.

System MoP for a given Concept of Operations

Verification by Methodology “Nested Games”

Real measurement data is necessary to ensure that the critical behavior is sufficiently well described for a follow-on extrapolation purpose.

System MoE for a given Concept of Operations

Verification by Methodology “Nested Games”

(*) For Validation: Avoid Criticality, analyze Benchmark Problems as nested Fair Games
Non-cooperative game
(Reasoning)

Details vs. Specifications

These two players have to come as fast as possible to a design decision with guaranteed resulting effectiveness for the actual system implementation.
Stochastic differential equation (SDE)
\[ dx(t) = f(x(t), t, a, b)dt + \sigma(x(t), t)dB(t), \quad x(t_0) = x_0 \]
Brownian motion process with drift and diffusion.

Player a wants to maximize, player b to minimize:
\[ \phi(x_0, t_0) = E \left[ \inf_{b(\cdot)} \sup_{a(\cdot)} \left( \int l(x(s), s, a(s), b(s))ds + g(x(T)) \right) \right] \]

Solution for expected costs (viscosity solution):
\[ D_t \phi(x, t) + H(x, t, \nabla \phi(x, t)) + \frac{1}{2} \text{trace} \left[ \sigma(x, t)\sigma^T(x, t) D^2_x \phi(x, t) \right] = 0 \]
with Hamiltonian
\[ H(x, t, p) = \max_a \min_b [pf(x, t, a, b) + l(x, t, a, b)] \]
• No connection between goals
• No dependence on actual movements (e.g. reachability)
• No dependence on specific observation (e.g. percolation)
• Deception

INDEPENDENCE PLAN (IP) in time and space, various combinations are possible
\[
F(X) + \sigma \eta(t) + \sum_{i=1}^{M} \beta_i IP_i
\]

• Meta-Level formula for movement of assets whereby \( \beta_i \) are Lagrange Multipliers such that the constraints of the Independence Plan (IP) are implemented.

• J. Honerkamp → Euler simulations even with multiplicative noise are possible (Renormalization)

The SSN Ontology as a (surprisingly) well fitting example for Multistatic Sonar.

http://www.w3.org/2005/Incubator/ssn/
Architecture Frameworks should be used to describe the “Details”-player.

http://megaf.di.univaq.it/megaf.html
• Change the parameters of Details associated to high costs

• Search for Independence Plan in associated POSG
  • Reject change for Details in case no Independence Plan available

• In this procedure:
  Start with independent agents, then trade dependence to gain efficiency
Reasoner Module decides on activation

Estimator

Controller

Independence Plan

POSTERIORI

EiV&V

Automatically constructed approximations

Real data from dedicated tests

Performance

Effectiveness

Efficiency

Trading:
Ontology & Independence Plan
Optimization

Ontology
Be honest ... testing costs!

\[ \phi(x, t) = E[\inf_{b(\cdot)} \sup_{a(\cdot)} (\int l_{IP}(x(x), x, a(s), b(s), IP(x, s)) ds + g(x(T))))] \]

- Cost function \( l_{IP} \) includes costs for Dedicated Tests.
- More analytic treatment, less tests!
- The more separation due to independence is generated, the more analytic treatment becomes possible.

Cost

Main component: equipment

Main component: testing

Best coordination design

Complexity
• Criticality (two sources of criticality at META LEVEL)
  → Details and Specification
  → If critical, then avoid this parameter region

• Relevance of information:
  • In this talk, the ESTIMATOR (i.e. processing of measurements) has not been in the focus of the discussion explicitly.
  • Measurements are modelled e.g. as $y(t) = h(x(t), u(t)) + N\nu(t)$
  • The constraint of EiV&V can be interpreted as a force to look for solutions where control actions need only to depend on sparse information about the environments, targets and partners → minimization of relevant hidden information.
Ref01: ICRA 2012 [2], L. Parker, Forming and Executing Coalitions of Heterogeneous Robots
Ref02: ICRA 2012 [2], T. Balch, Learning Multiagent Hybrid Controllers from Animal Observation
Ref03: ICRA 2012 [2], M. Steinberg, Swarms: Moving from Theory to Practice
Ref04: ICRA 2013 [3], J. Durham, Many Robot Systems as the Engine of Ecommerce
Ref05: ICRA 2013 [3], E. Olson, Humans and Multi-Robot Systems
Ref06: ICRA 2013 [3], R. Arkin, Robots that Need to Mislead
Ref07: ICRA 2014 [4], L. Sabattini: Decentralized Control of Networked Systems for Setpoint Tracking
Ref08: ICRA 2014 [4], C. Secchi: Passivity-based Teleoperation of Multi-Robot Systems with Time-Varying Topology
Ref09: IROS 2014 [4], P. Dames: Localizing Large Numbers of Targets without Data Association using Teams of Mobile Robots
Ref11: IEEE TASE Special Issue [1], Szwaykowska et al
Ref12: IEEE TASE Special Issue [1], Cepeda-Gomez et al
Ref13: IEEE TASE Special Issue [1], Shi et al
Ref14: IEEE TASE Special Issue [1], Cap et al
Ref15: RSS Workshop, F. Ehlers, D. Sofge, L. Sabattini

• Multistatic Sonar

• Fish and Whales, (Deception e.g. 4 slits, or net )
Result for Multistatic Sonar

- Add more sources to coordinate more receivers to have more chances to detect in smaller area.
- Add more receivers to have more chances to detect in the smaller detection area.
- Due to bad weather at the receivers the size of the detection area is getting smaller.

→ Calculation of how many sources and receivers are needed via adding independent surveillance layers to compensate for smaller detection area.
• Exact calculations depend very much on the specific rules of the game (which have not been presented in this talk in detail),

• However: Important here for this talk is that an analytic treatment is possible by the described methodology

→ Extensions by taking this as a prototype for other team coordination design decisions.
Challenge: Mapping between MoPs and MoEs

Reasoning as a non-cooperative game between ‘Details’ and ‘Specifications’ with the constraint to allow an Efficient independent (EiV&V) process.

Generation of an “Independence Plan” to support EiV&V

Iterative optimization algorithm to generate more efficient implementations while maintaining effectiveness.

Scalability as inherent part of this methodology, e.g.:
- Multistatic sonar for larger surveillance regions
- the “Fish & Whales” example with more agents
• Citation from Russ Tedrake’s Keynote: “Optimization for Robust Motion Planning and Control”, 1 Oct., IROS 2015 [http://www.iros2015.org/index.php/program/keynotes]:
  • These systems must plan in real time in novel environments, and be robust enough to deal with uncertainty from perception, imperfect actuators, and model errors.
  • Making these optimizations tractable requires exploiting sparsity and convexity in our robot equations, and making informed relaxations.

• Translation/ to Coordination Design
  • Sparsity → Minimize relevant hidden information
  • Convexity → Criticality (make sure system is stable)
  • Informed relaxations → Independence (change only if no harm)