WTD 71

Bundeswehr Technical Centre for
Ships and Naval Weapons,
Naval Technology and Research

FWG – Research Department for
Underwater Acoustics and Marine Geophysics

On-line Reasoning about Coordination Design Decisions

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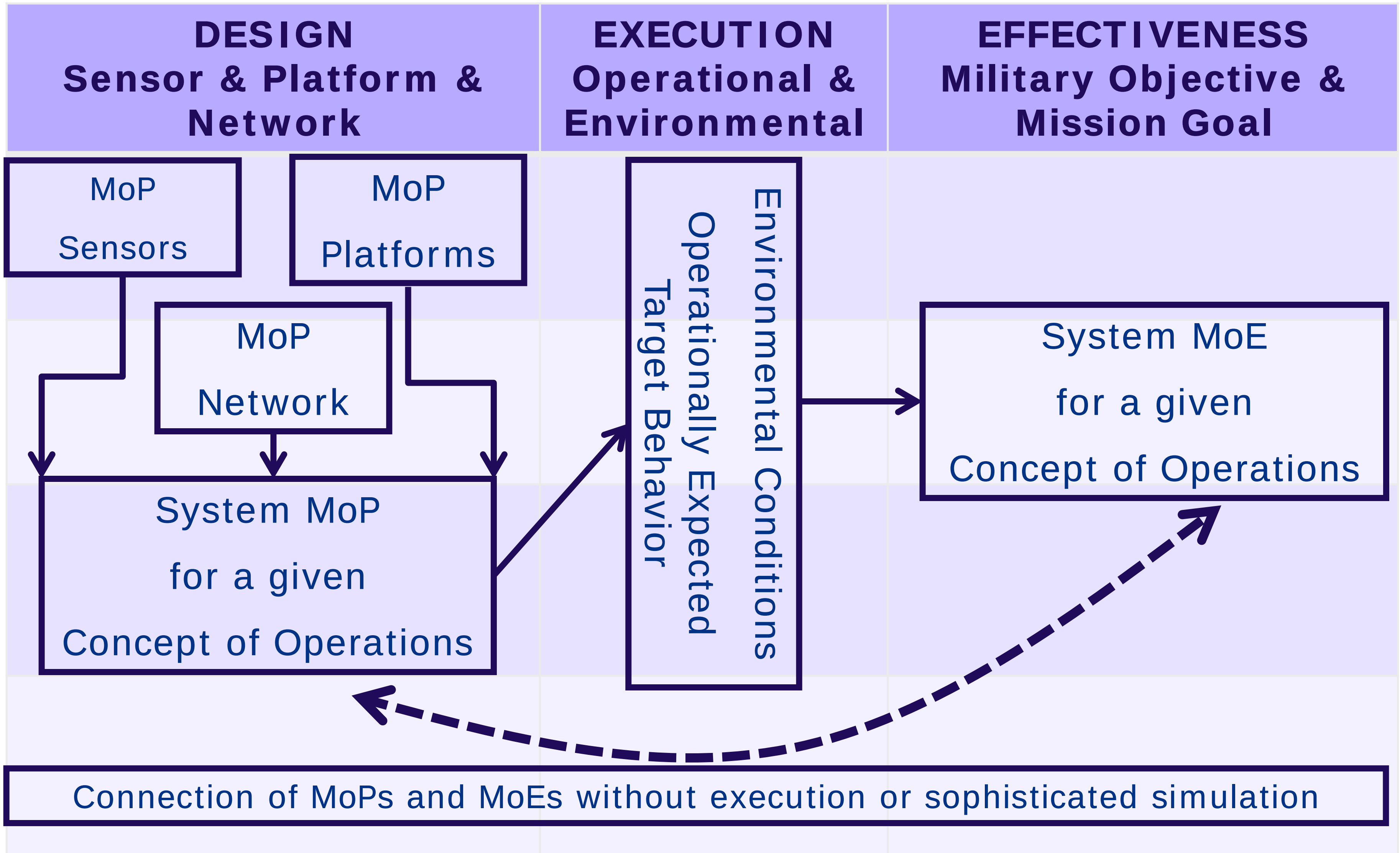
Outline

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



MoPs, MoEs and ...

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.

http://ftp.rta.nato.int/public/PubFullText/RTO/AG/RTO-AG-300-V28/AG-300-V28-ANN-B.pdf

Challenge

- 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).

Overarching Concept for Decision Making

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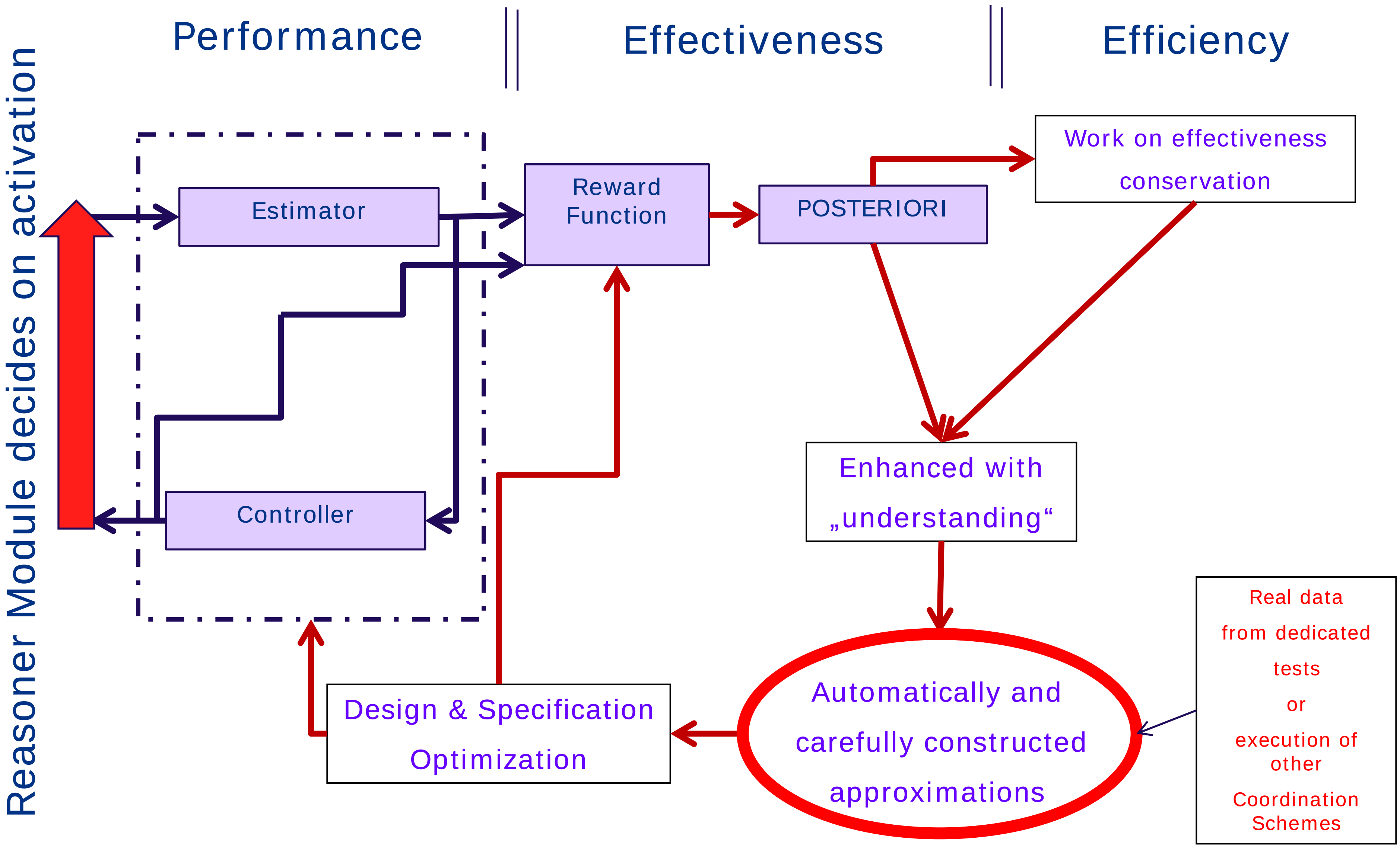
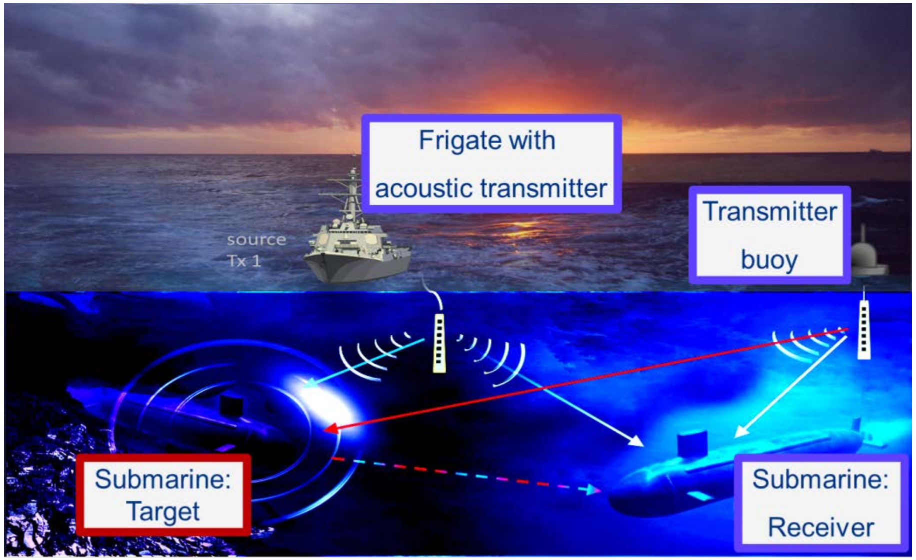


Examples (Start)

- Multistatic Sonar

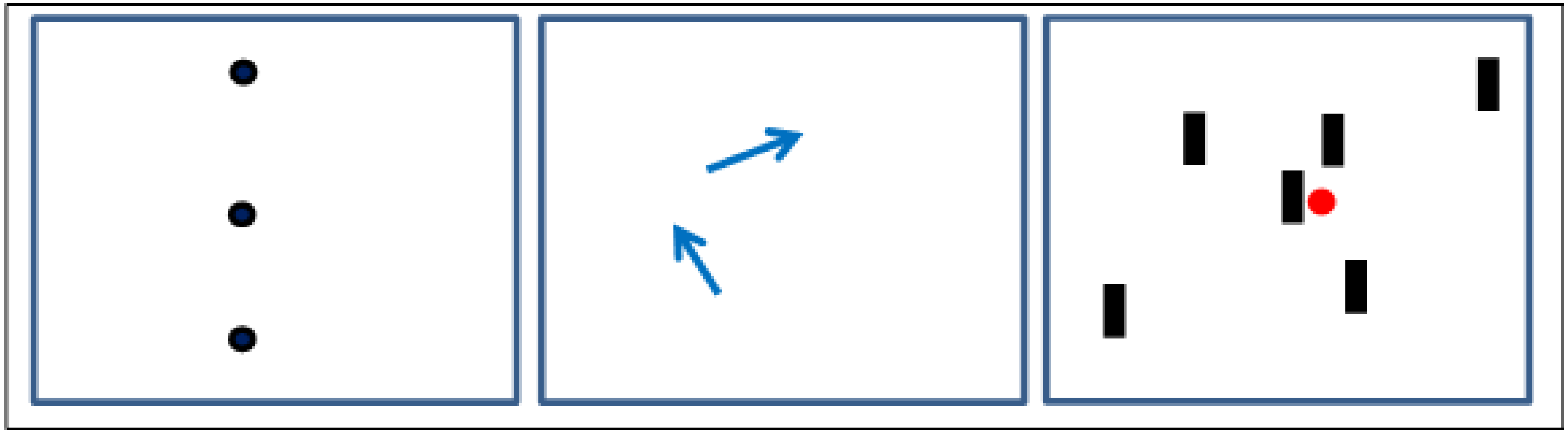


M. Brötje, F. Ehlers, M. Ulmke, Maritime Aufkärung: Multistatisches Aktiv-SONAR und Passiv-RADAR, Europäische Sicherheit und Technik, 6/2014.

- Fish and Whales

http://hdwpics.com/humpback-whale-hdw2596298, http://hdwpics.com/sea-swarm-fish-sealife-h

Multistatic Sonar Test Bed



Stand-off SOURCES

AUVs as receivers

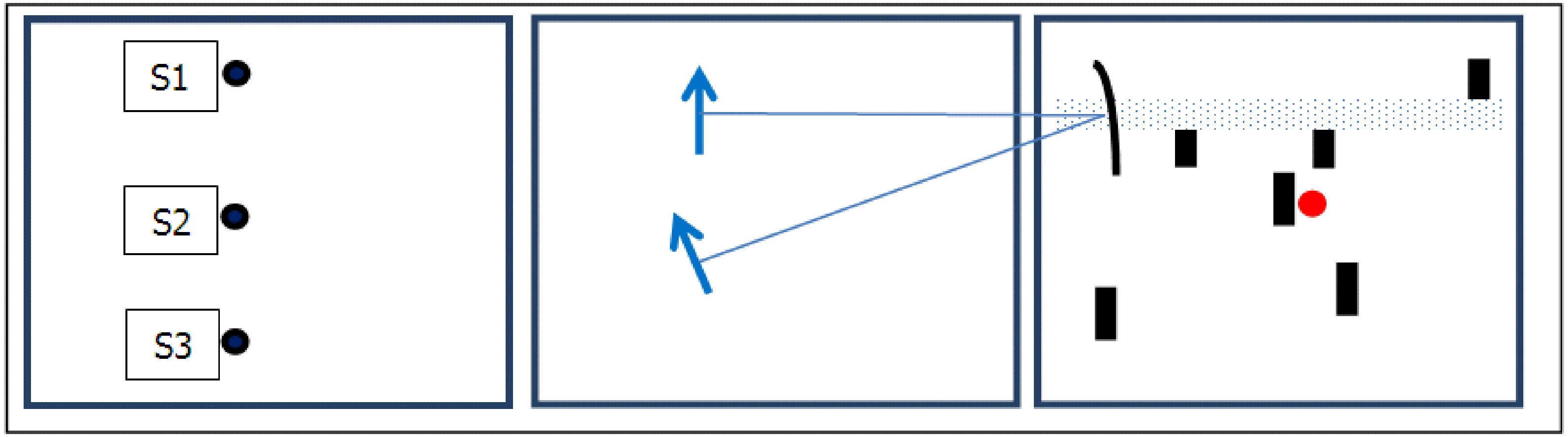
Clutter

Target

- 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.

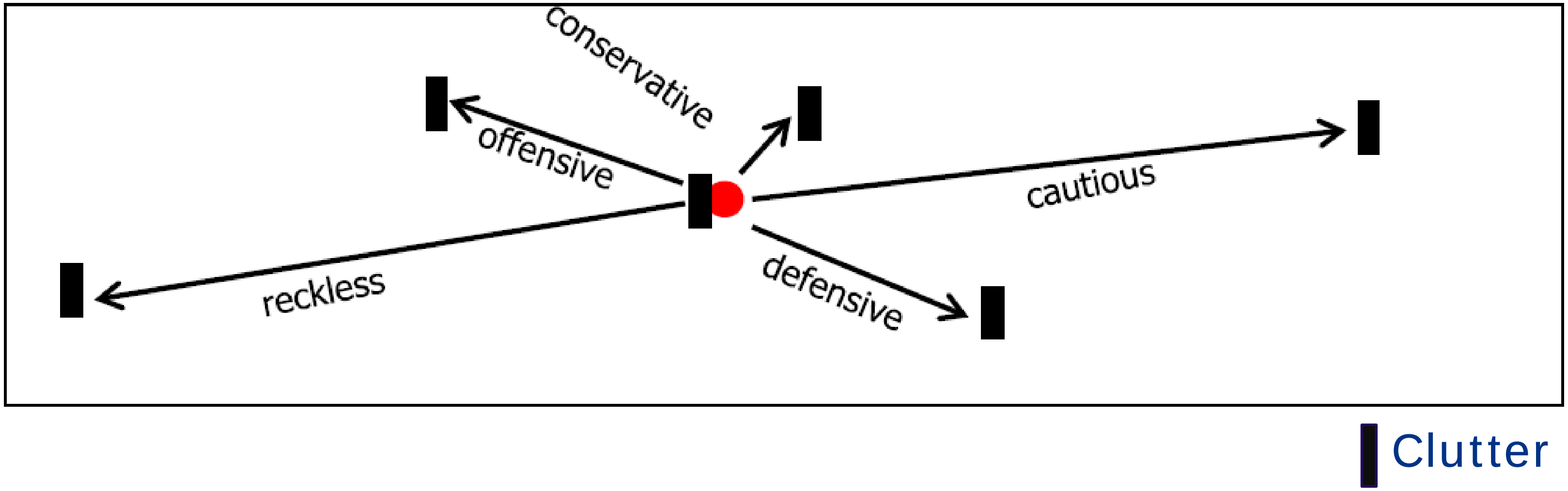
Coordination of Receivers



- 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.

"Mental States" of the Target

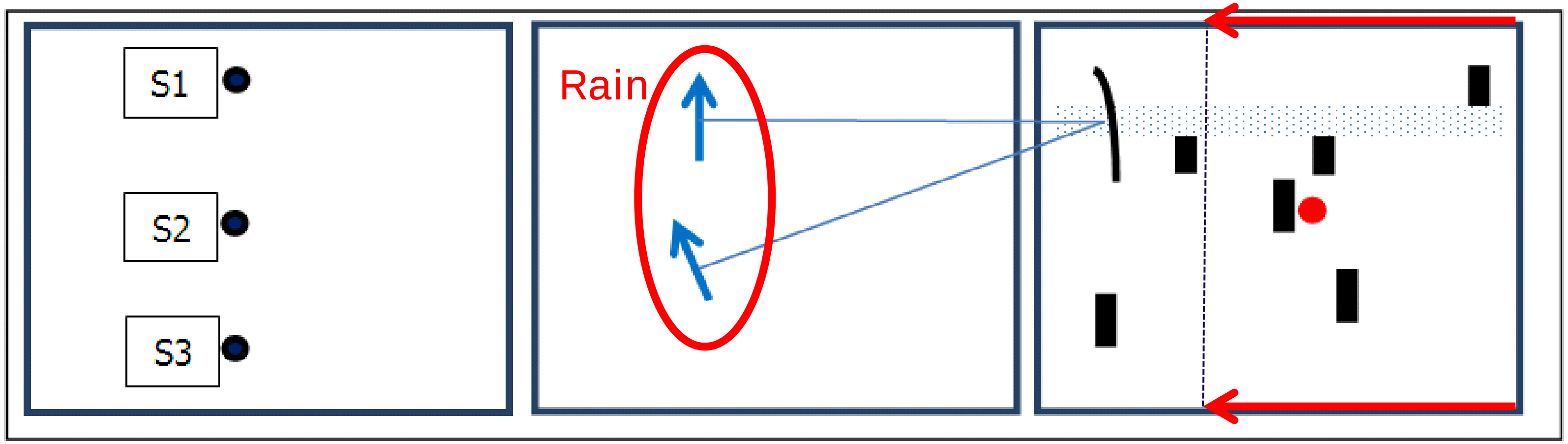


- Optimization of target behavior: Hide at clutter points
- For the surveillance it is not possible to know in which "Mental State" the target is, but the surveillance is able to geometrically take away degrees of freedom from the target.

→ Idea for coordination design for the surveillance:

Minimization of relevant hidden information

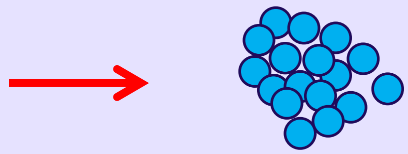
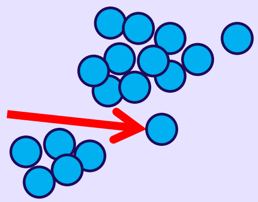
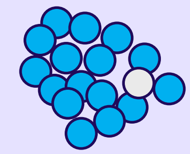
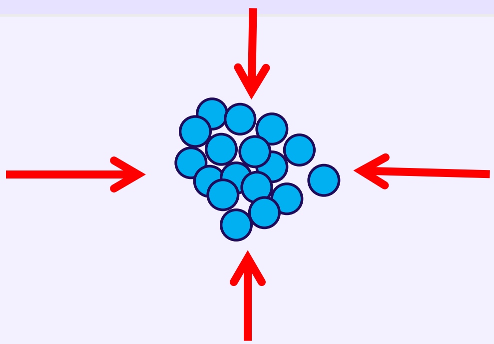
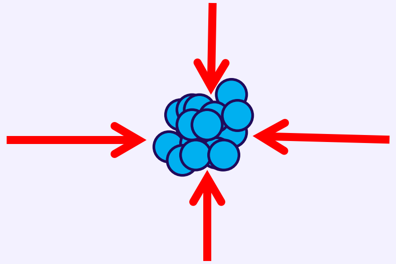
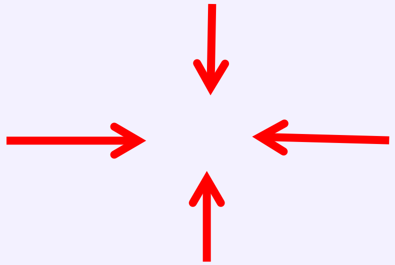
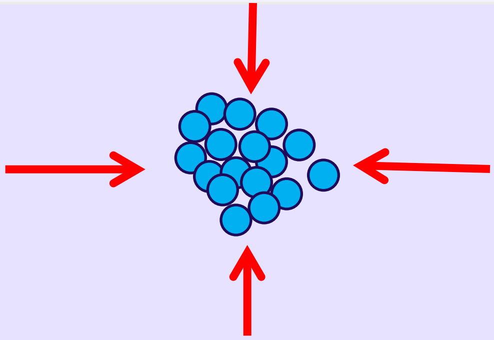
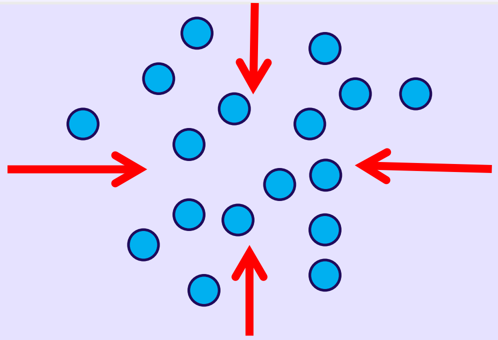
Adaptation to Changes in the Environment



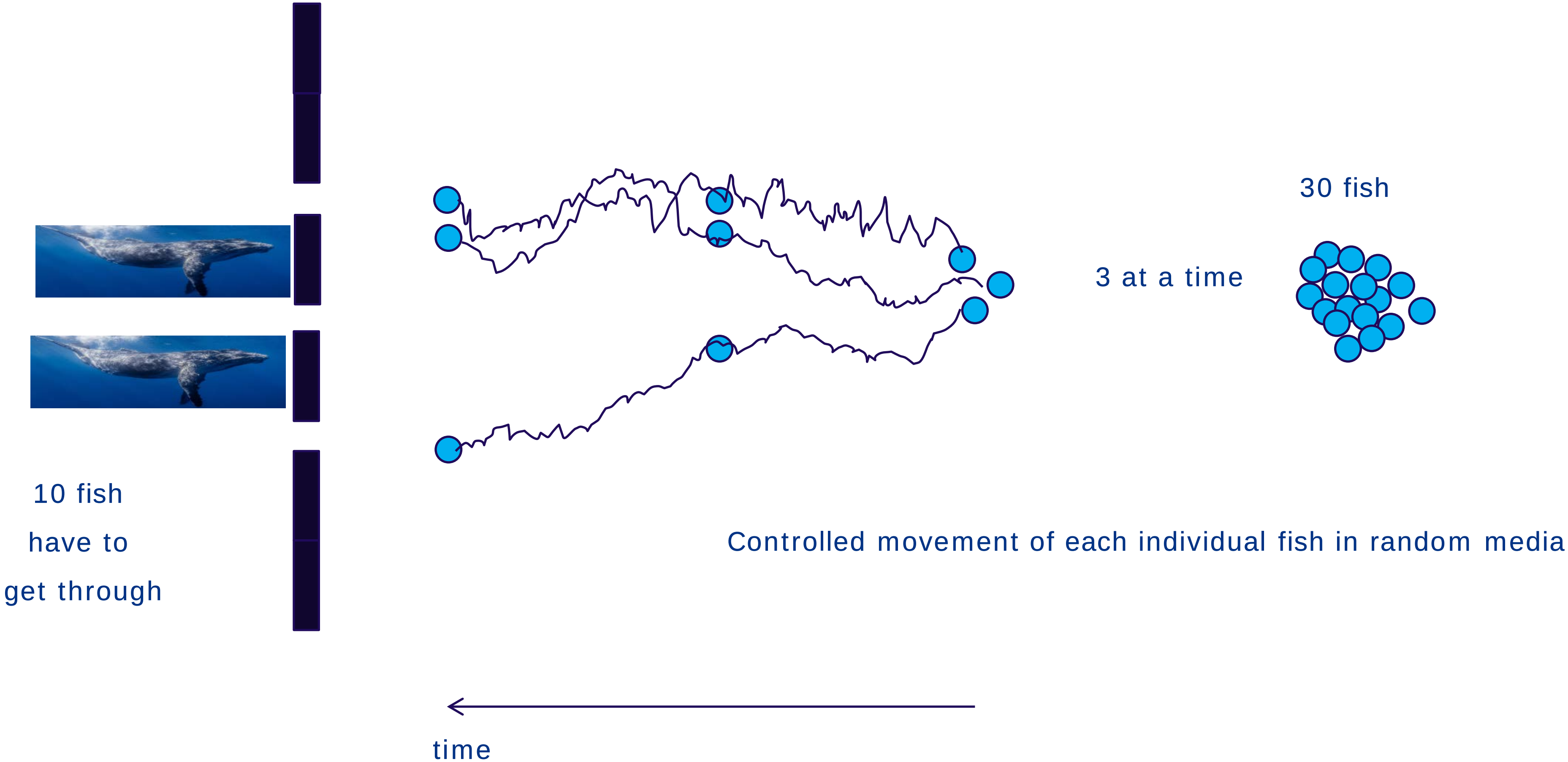
- The red arrows indicate a shrinking size of the surveillance area, due to suddenly occurring rain.

- 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

Game Setup	Execution	Winner (in terms of energy)
		
		
		?

Objective: START with 30 fish at the right, make sure 10 fish make it through



Stochastic Optimal Control

For a double slit experiment:

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

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

$$J(x,t) = \min_u C(x,t,u(t))$$

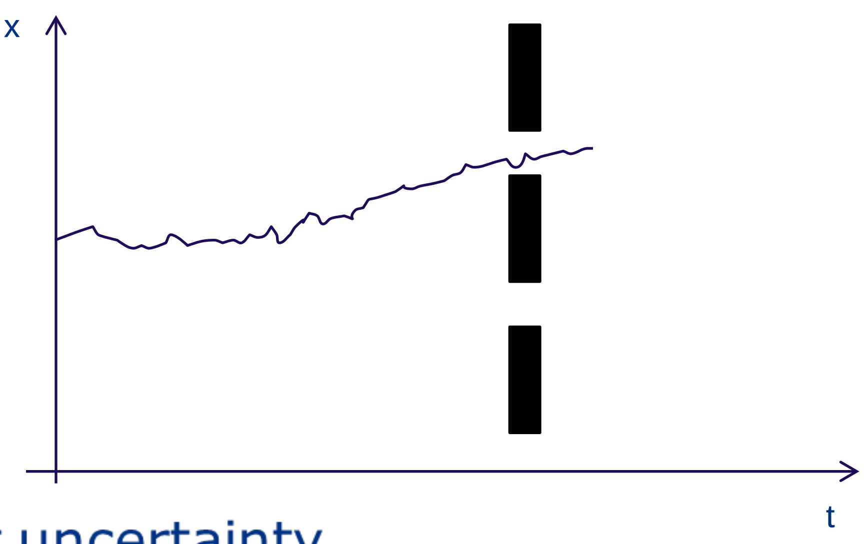
→ Hamilton-Jacobi-Bellmann

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

→ Cost-to-Go for small slit size

→ Multi-modal decision making at a critical time t_c

→ Binary channel for measurement uncertainty.

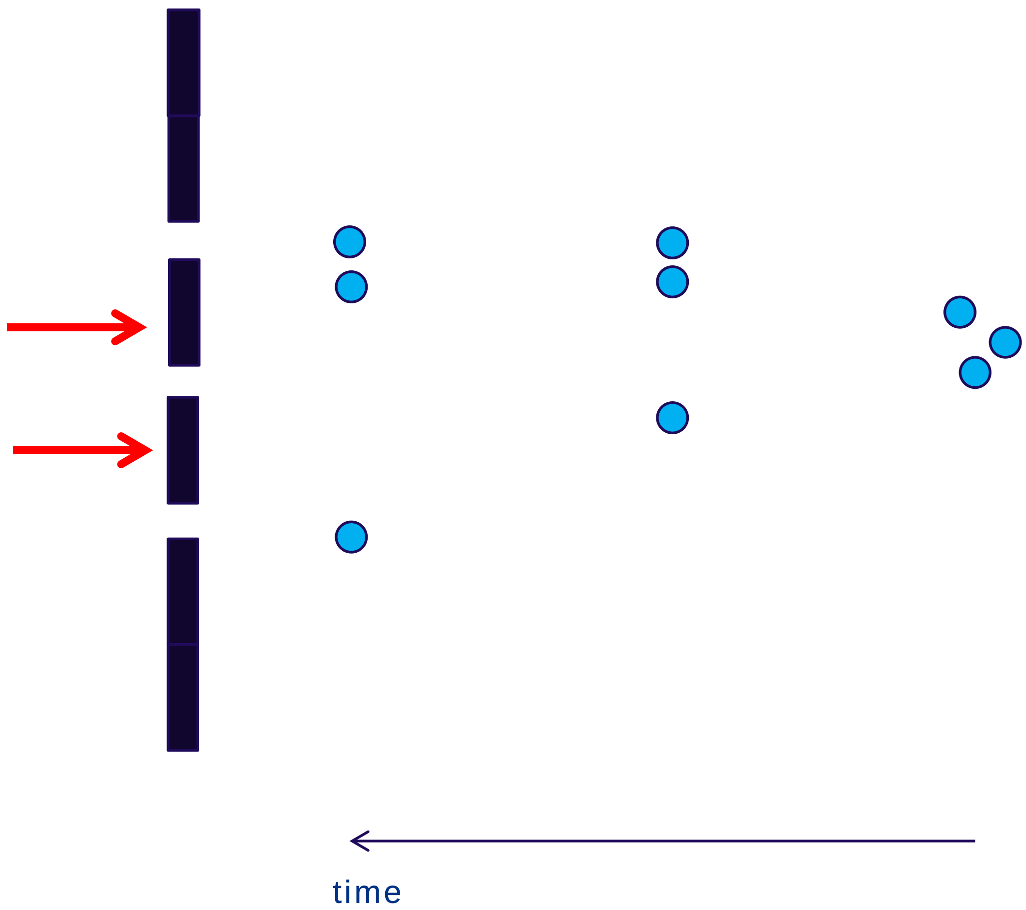


➔ Analytic description of control & sensing

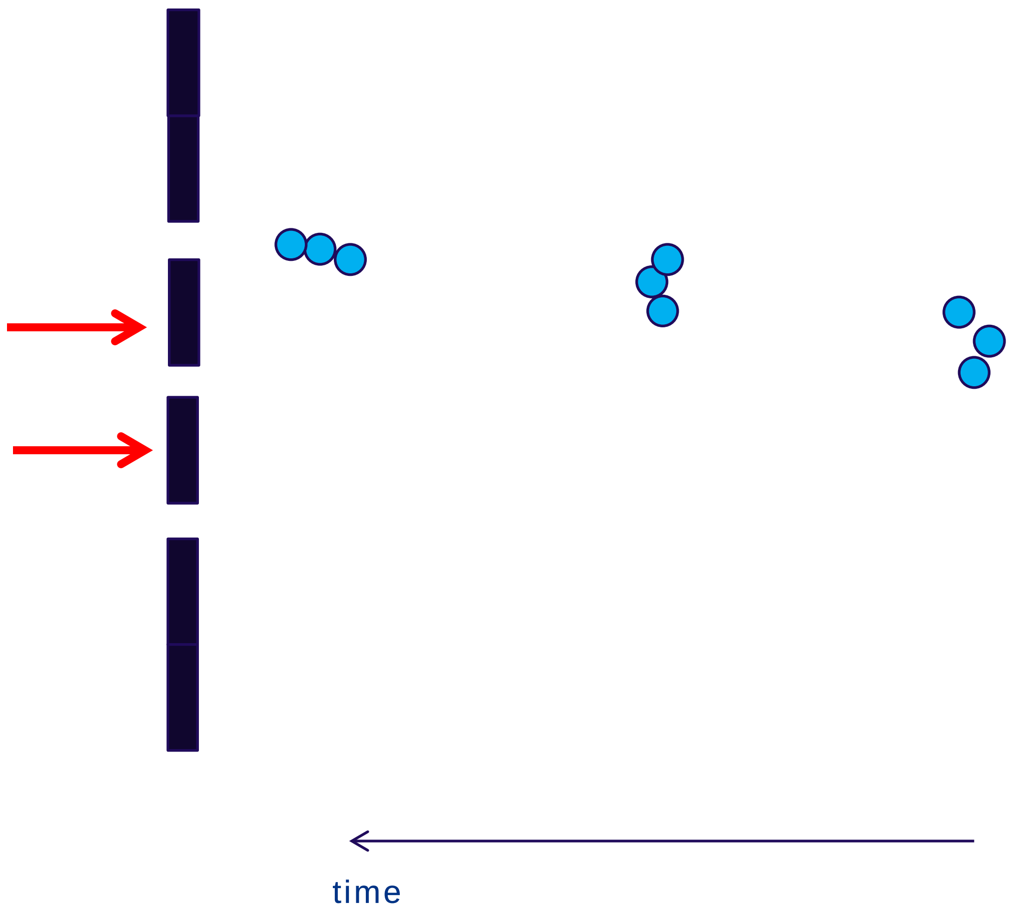
Challenge for the Fish & Whales Example

- 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.

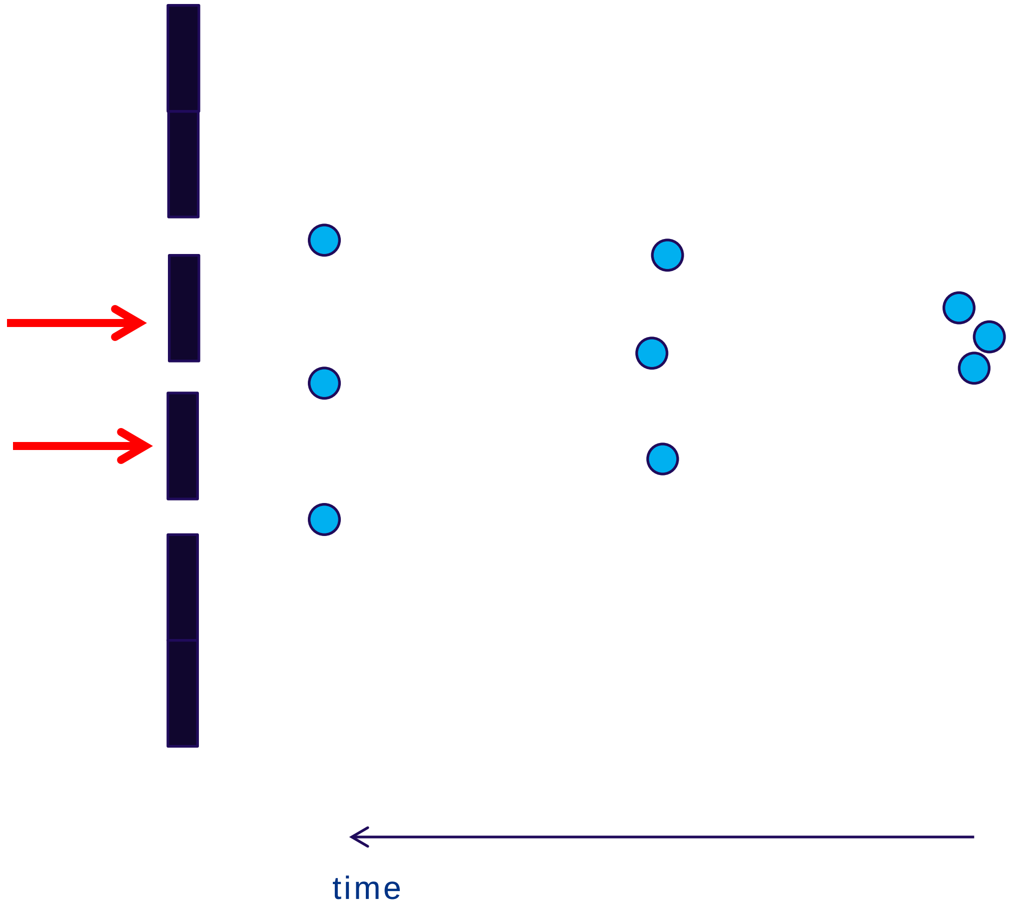
Coordination Design: Individuals



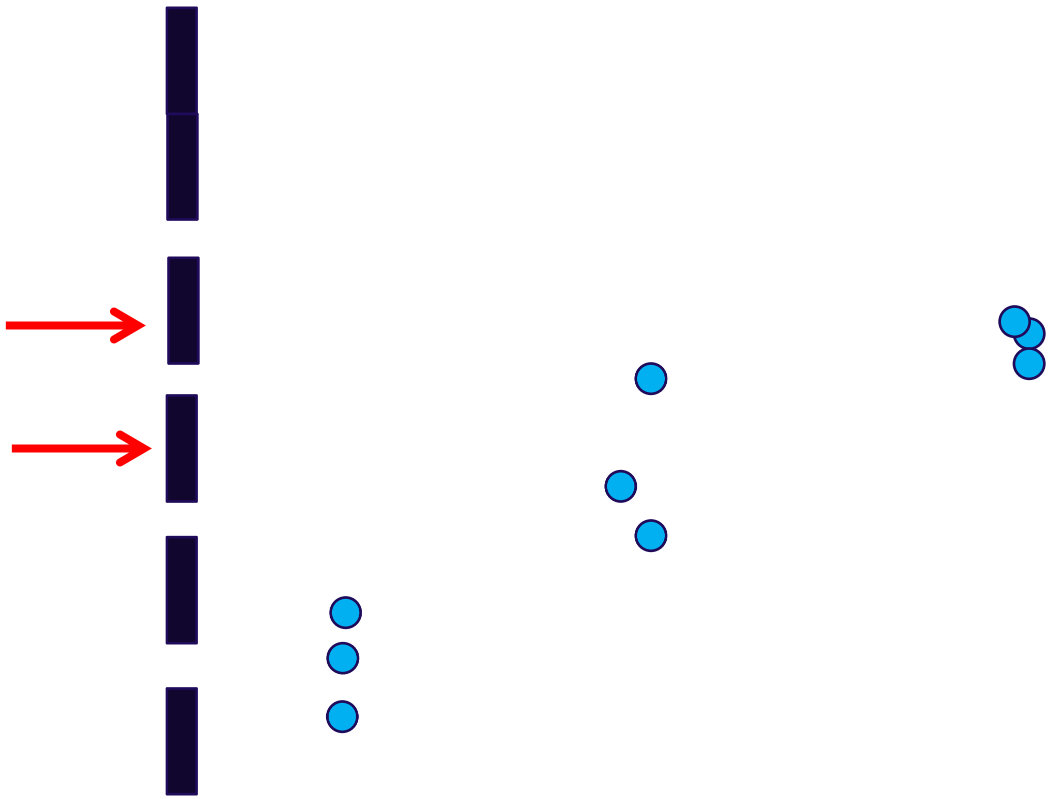
Coordination Design: Hierarchy



Coordination Design: Swarm



If the whales do not know about the existence of 4th gap.



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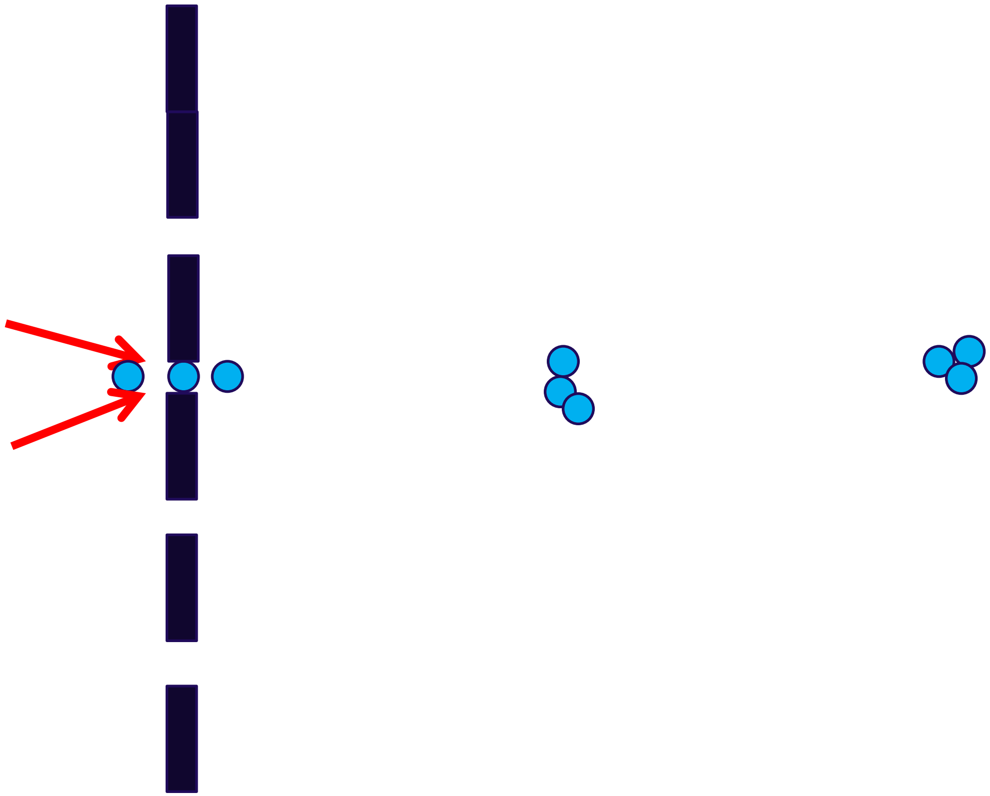
If whales do not eat the fish, the systems are decoupled.



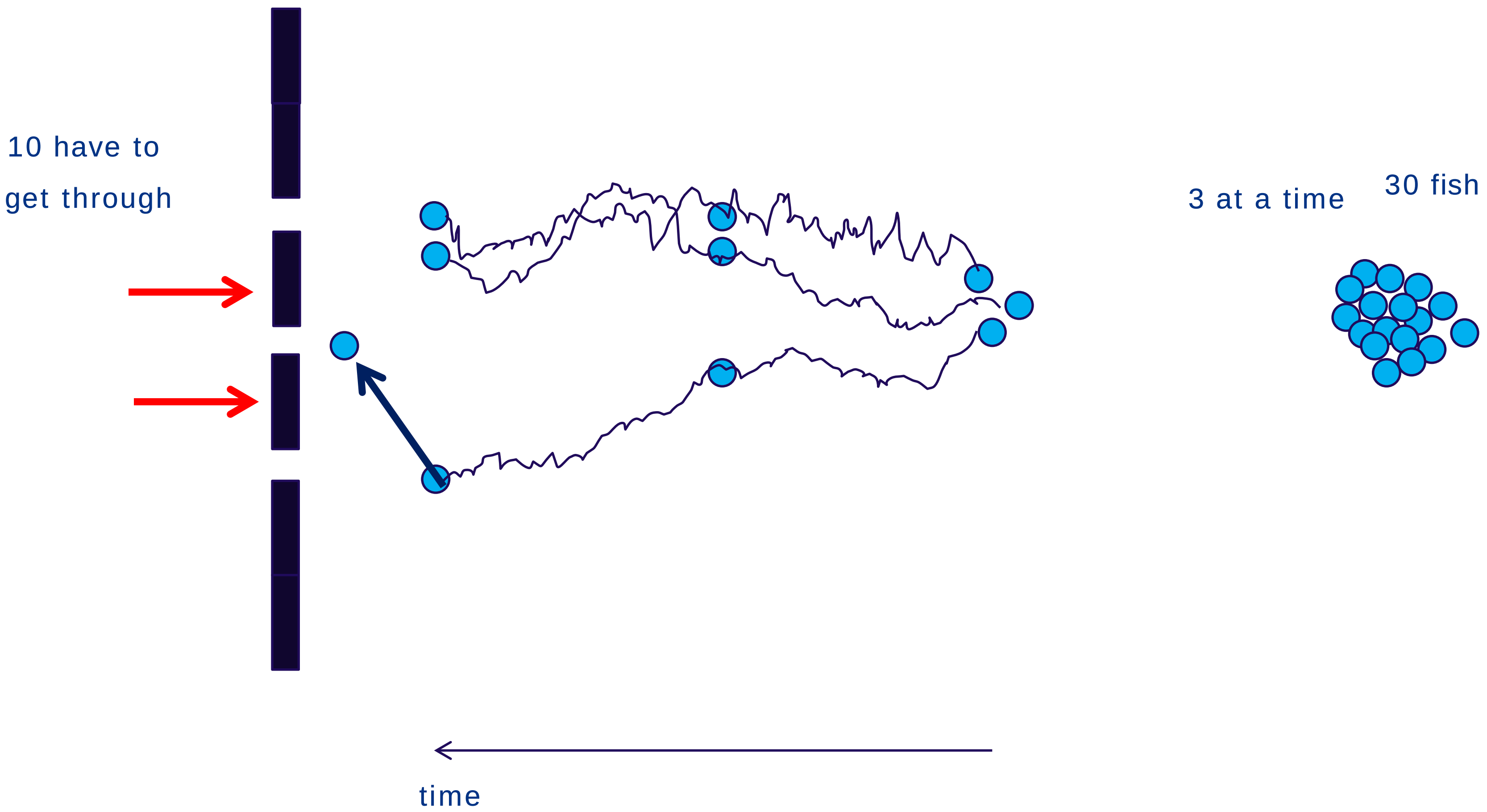
Observations from Fish & Whales Example

- 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

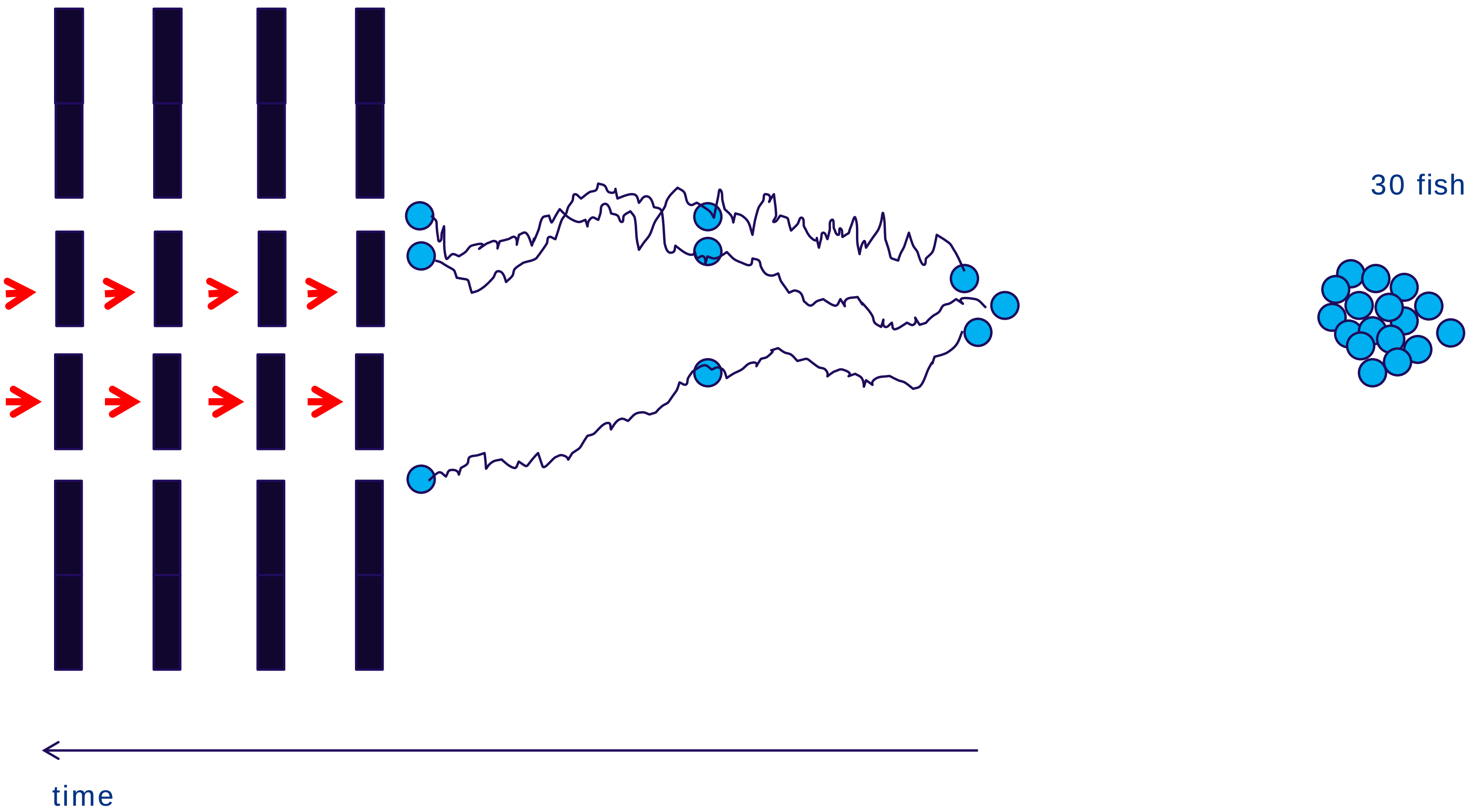
  \+ hypothetically
  - Independence in terms of terminal condition possible
  - Independence of prior modelling: Deception

- 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

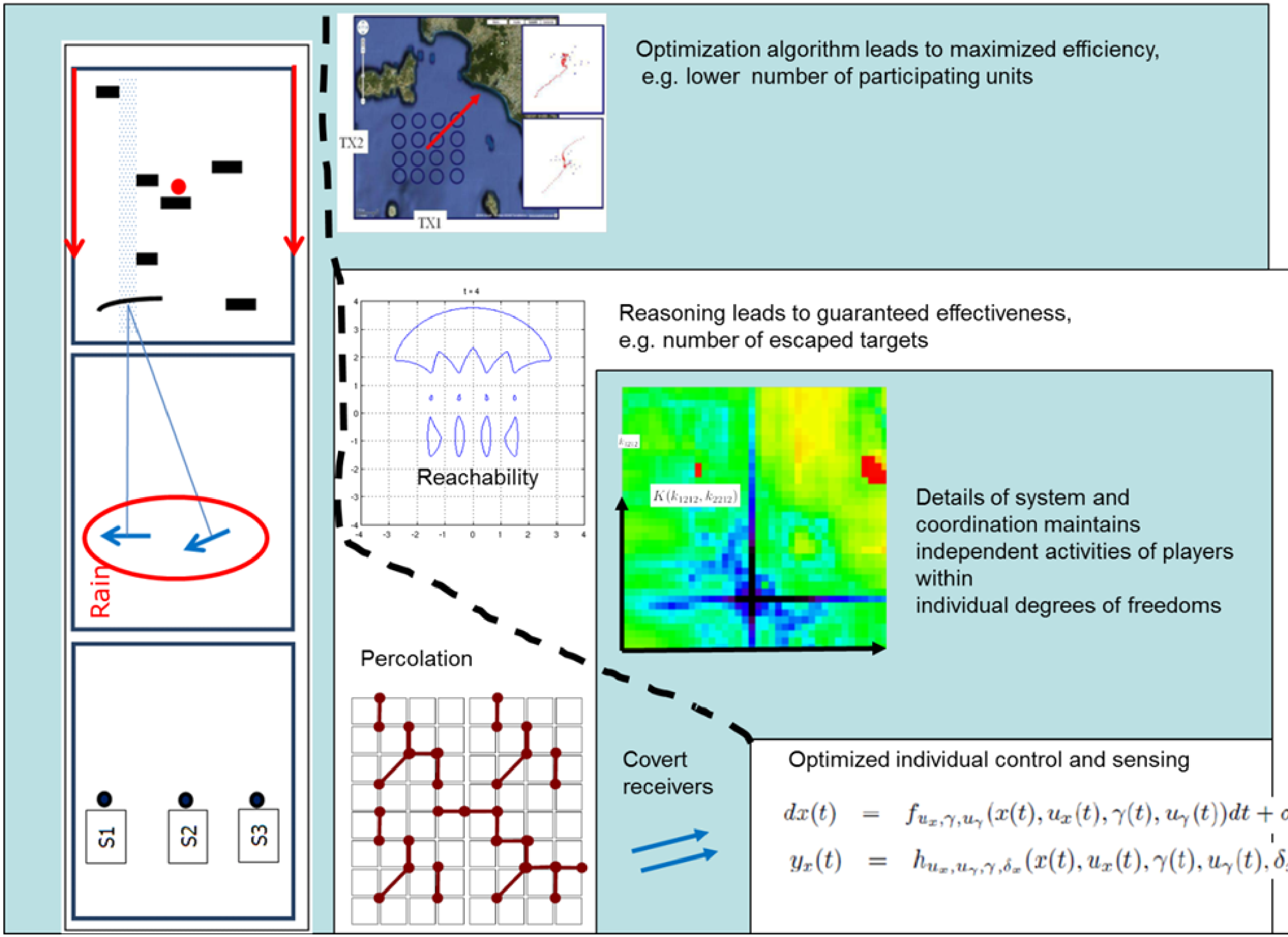
Reachability aspect: changes are not always possible



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

$$
\begin{aligned}
dx(t) &= f_{u_x,\gamma,u_\gamma}(x(t), u_x(t), \gamma(t), u_\gamma(t))dt + \sigma_x(x(t))d\omega_x(t) \\
y_x(t) &= h_{u_x,u_\gamma,\gamma,\delta_x}(x(t), u_x(t), \gamma(t), u_\gamma(t), \delta_x(t)) + N_x\nu_x(t))
\end{aligned}
$$

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.

How to find solutions "AUTOMATICALLY"?

From the examples:

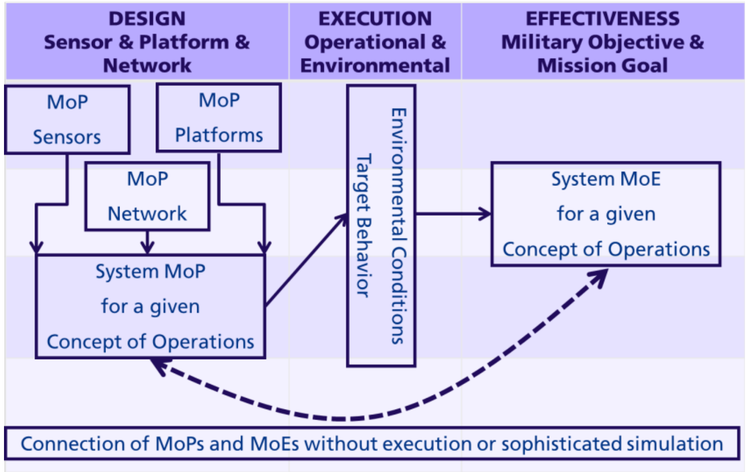
- (i) Minimization of relevant hidden information
- (ii) Independence
- (iii) Guaranteed reach of terminal condition
- (iv) Distributed decision making

➔ Inserting

Efficient independent Verification and Validation (EiV&V)

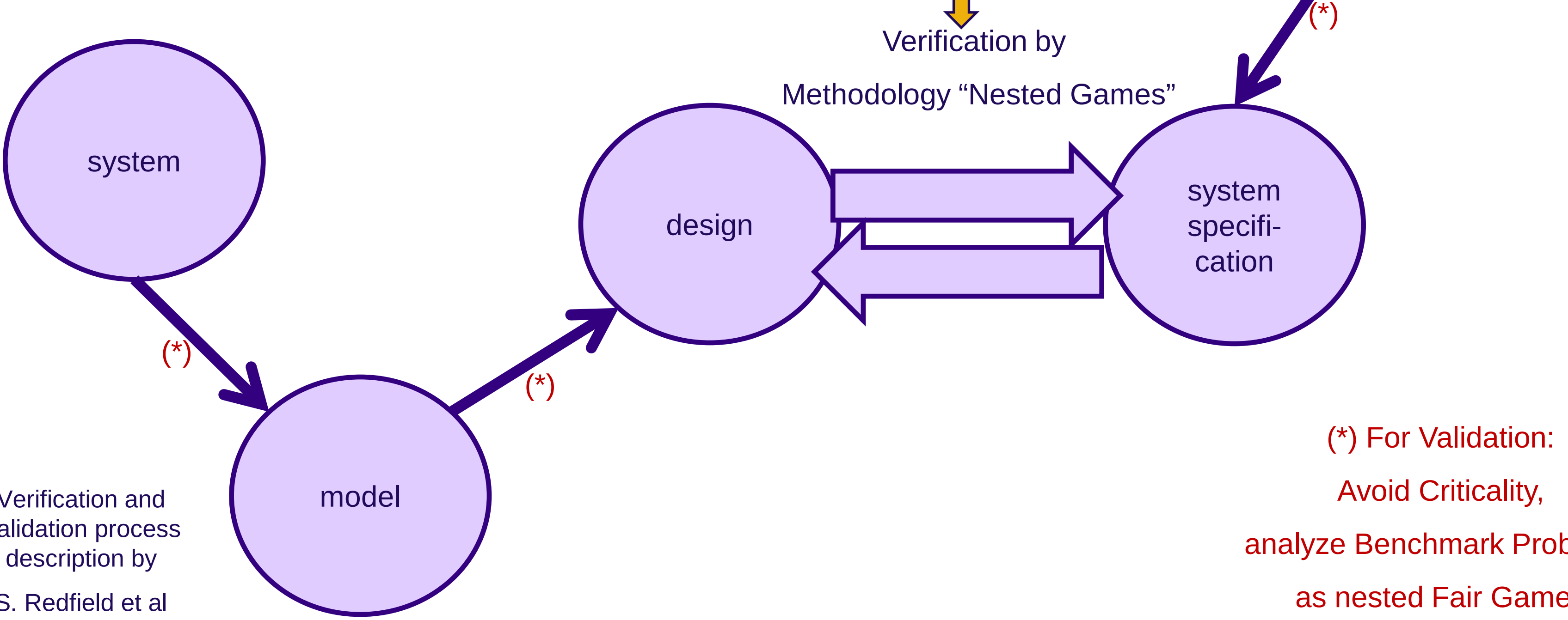
as constraint into the Stochastic Differential Game.

Entering iV&V Process



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

Goal-driven. i.e. starting from Mission Goal



Verification and Validation process description by

S. Redfield et al

(*) 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 Game

Stochastic differential equation (SDE)

$$dx(t) = f(x(t), t, a, b)dt + \sigma(x(t), t)dB(t), \qquad x(t_0) = x_0$$

Brownian motion process with drift and diffusion.

Player a wants to maximize, player b to minimize:

$$\phi(x_0, t_0) = E\left[\inf_{b(\cdot)} \sup_{a(\cdot)} \left(\int l\big(x(s), s, a(s), b(s)\big)ds + g(x(T)\right)\right]$$

Solution for expected costs (viscosity solution):

$$D_t\phi(x,t) + H\big(x, t, \nabla\phi(x,t)\big) + \frac{1}{2} trace\left[\sigma(x,t)\sigma^T(x,t)\, D_x^2\, \phi(x,t)\right] = 0$$

with Hamiltonian

$$H(x,t,p) = \max_a \min_b [pf(x,t,a,b) + l(x,t,a,b)]$$

Inspection of State-Space → Looking for Independence

- 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

Constraint in EiV&V

$$F(X) + \sigma\,\eta(t) + \sum_{i=1}^{M} \beta_i IP_i$$

- Meta-Level formula for movement of assets whereby β_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)

J. Honerkamp, Stochastische Dynamische Systeme, pp.183, VCH, 1990.

Ontology to Handle Details

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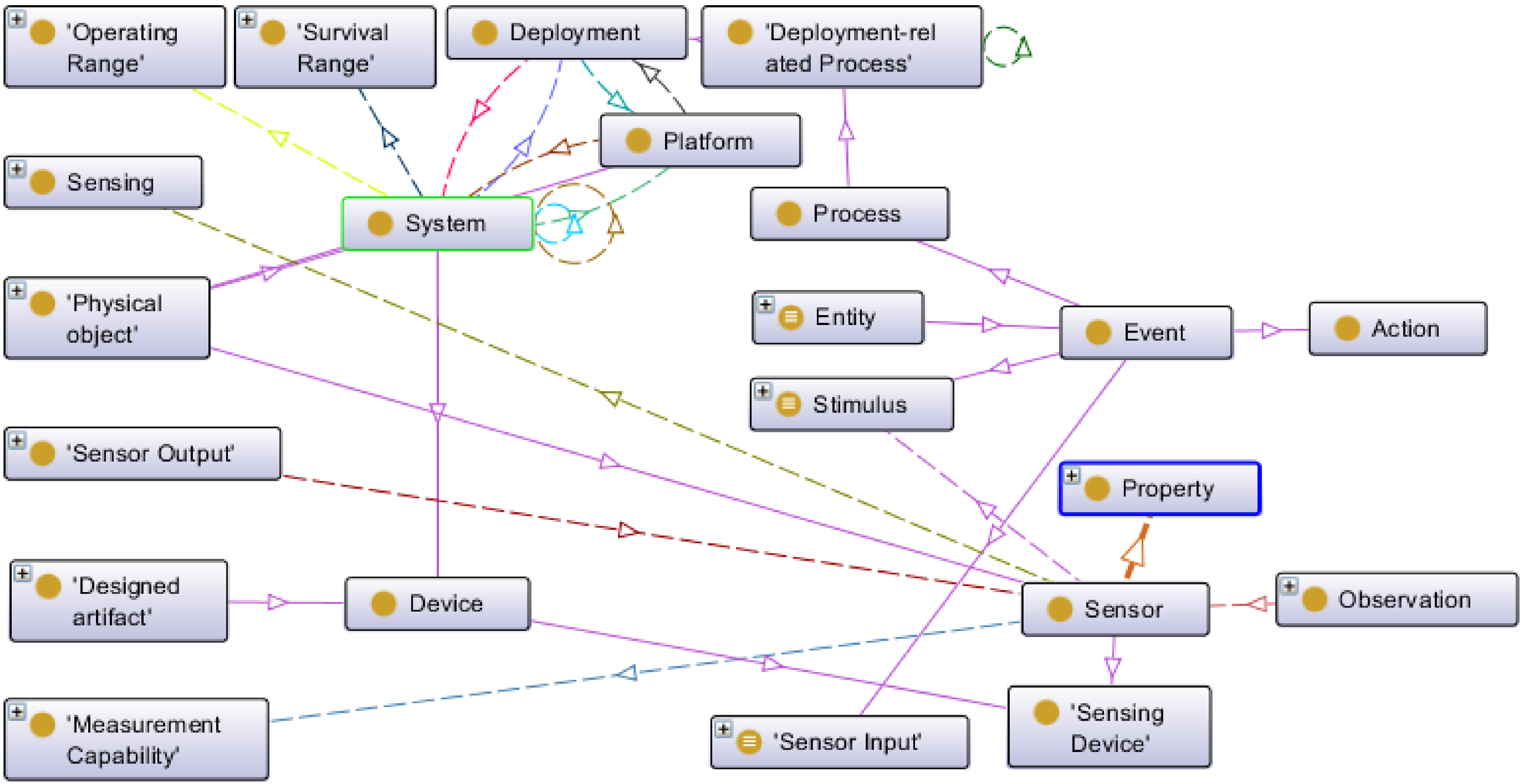
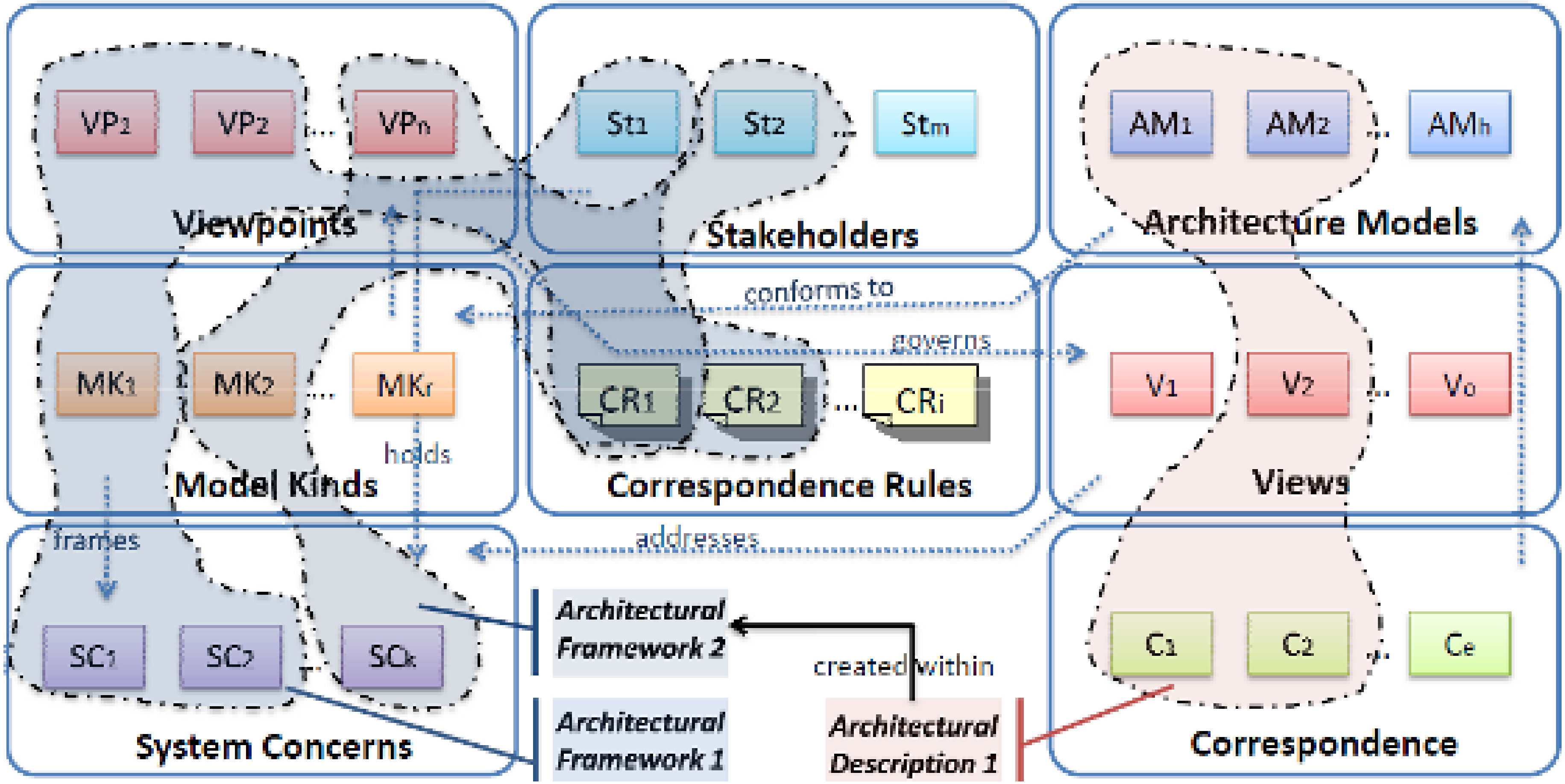
The SSN Ontology as a (surprisingly) well fitting example for Multistatic Sonar.



http://www.w3.org/2005/Incubator/ssn/

Architecture Frameworks

Architecture Frameworks should be used to describe the “Details”-player.



http://megaf.di.univaq.it/megaf.html

Trading Dependence against Efficiency

- 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

EiV&V inserted into Overarching Concept

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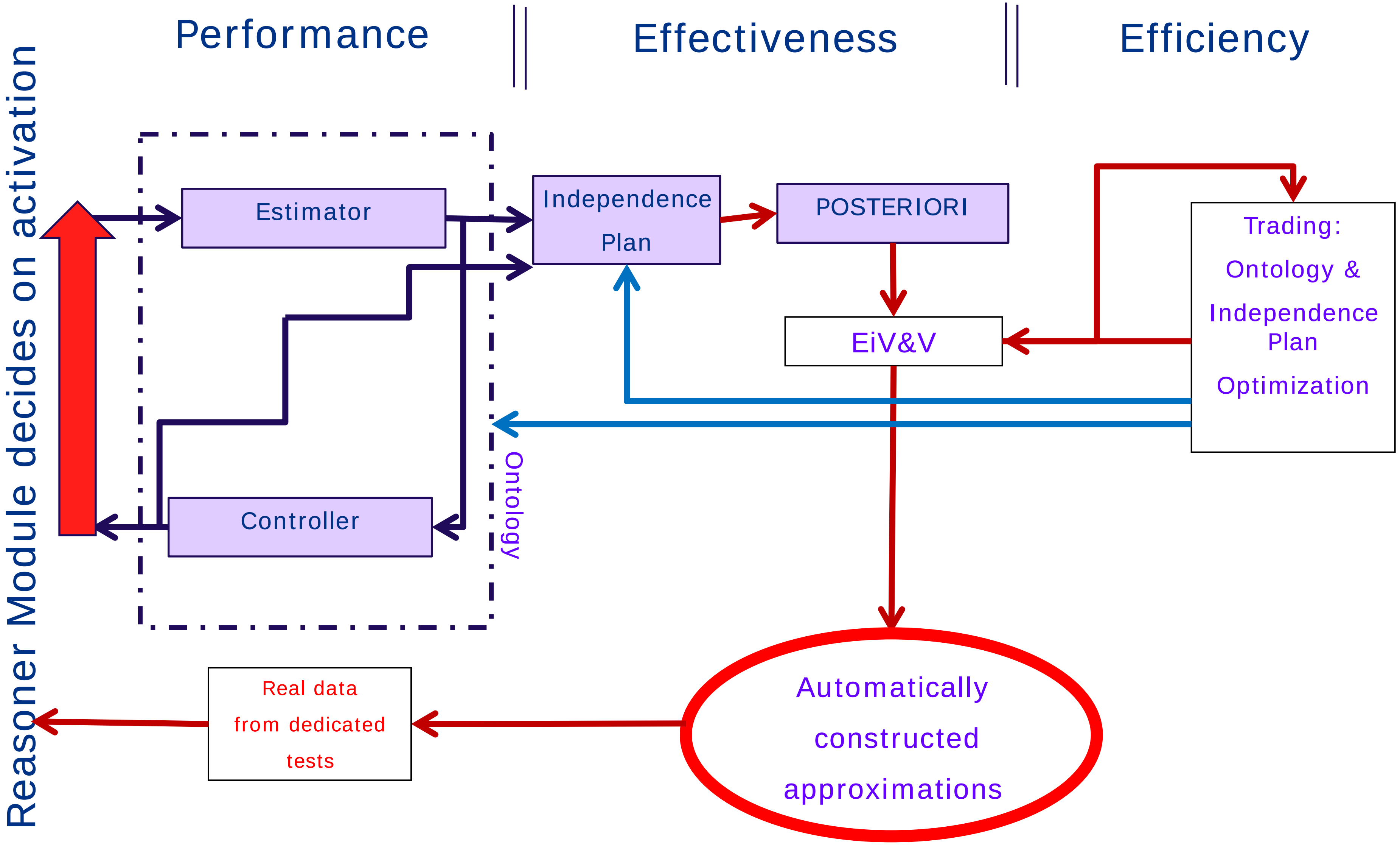
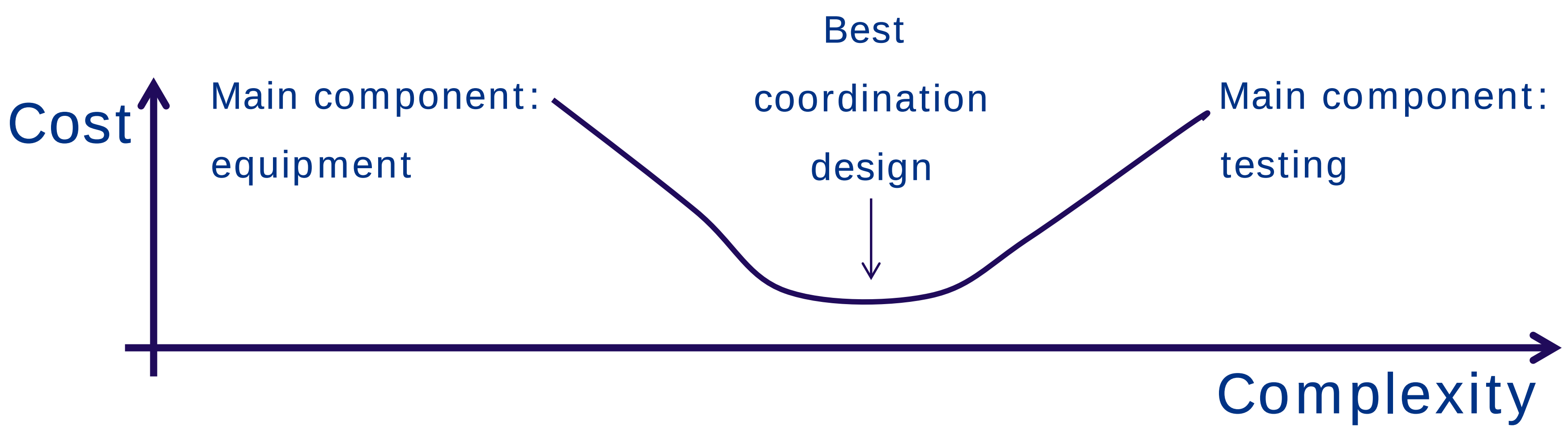


Be honest ... testing costs!

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

- 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.



Criticality / Relevance

- Criticality (two sources of criticality at META LEVEL)

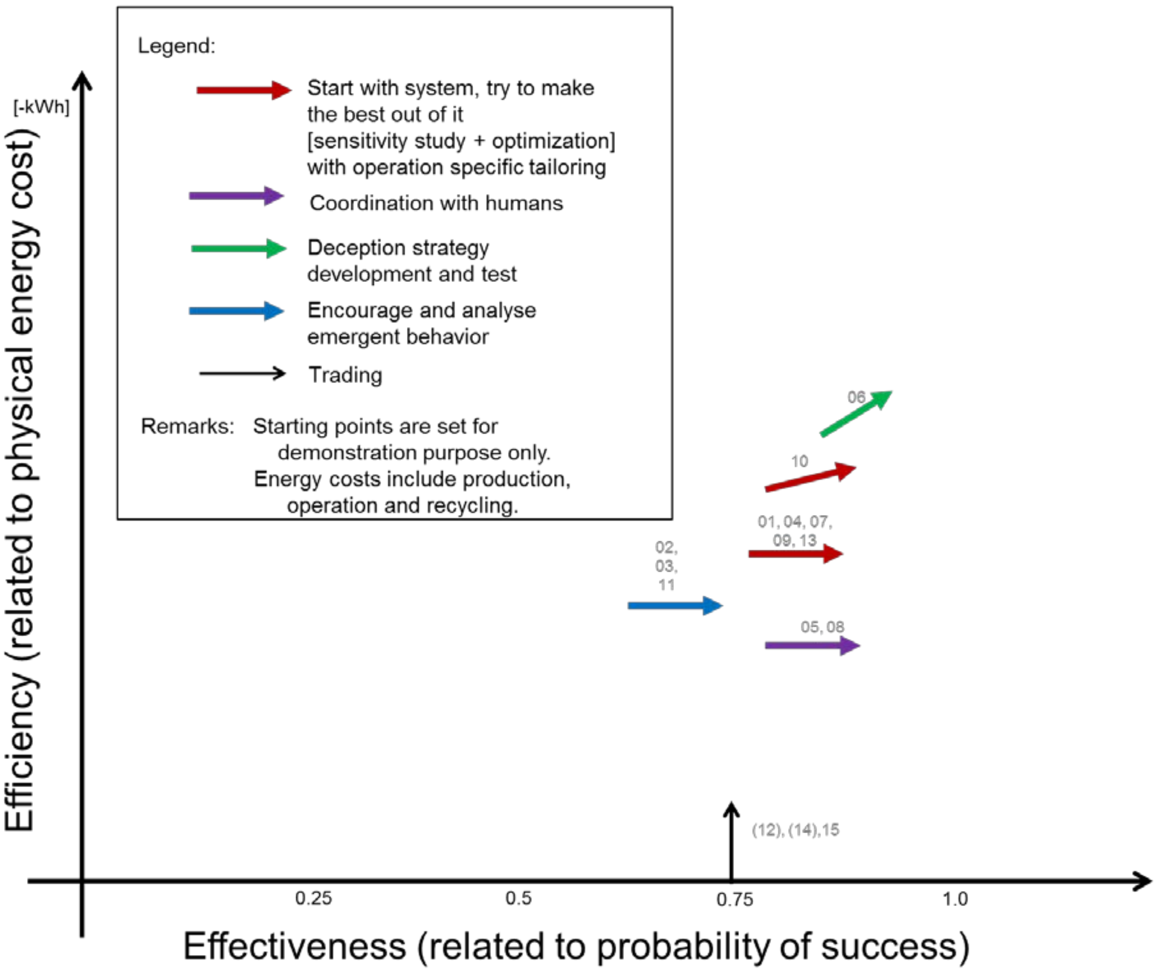
→ Details and Specification

→ 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 $y(t) = h\big(x(t), u(t)\big) + N\nu(t)$
  - 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.

Effectiveness / Efficiency Plane

Result of first categorization attempt



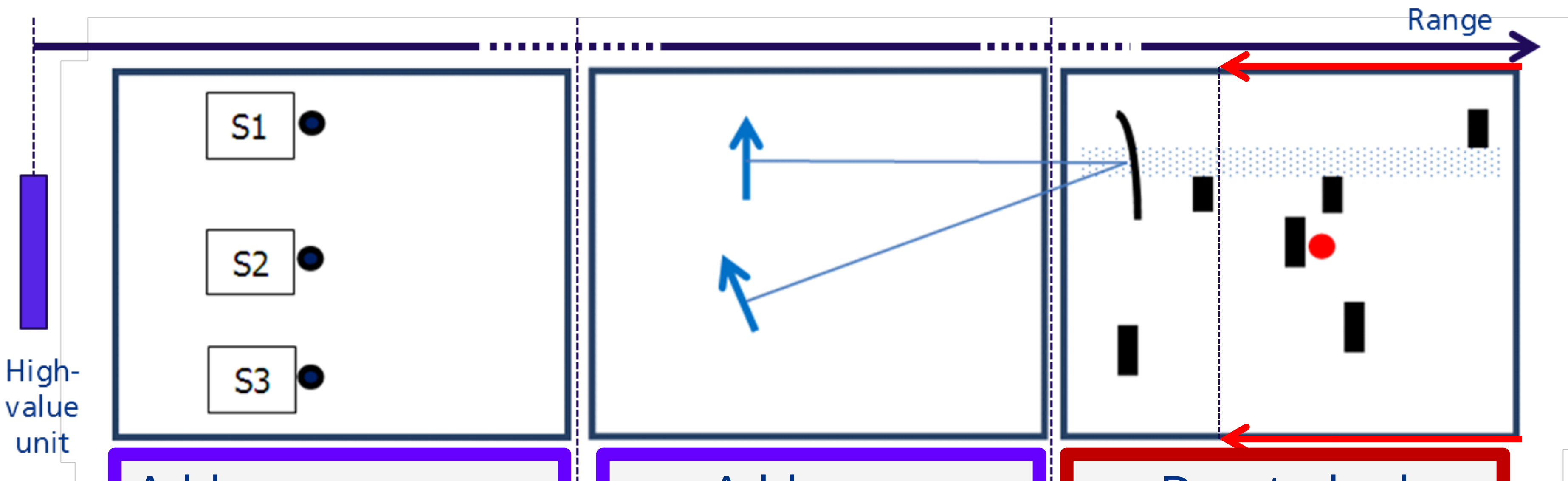
Ref01: ICRA 2012 [2], L. Parker, Forming and Executing Coalitions of Heterogeneous Robots
Ref02: ICRA 2012 [2], T. Balch, Learning Multiagent Hybrid Controllers from Animal Observation
Ref03: ICRA 2012 [2],, M. Steinberg, Swarms: Moving from Theory to Practice
Ref04: ICRA 2013 [3], J. Durham, Many Robot 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
Ref10: IEEE TASE Special Issue [1] Wallar et al
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

[1] IEEE Trans. On Automation Science and Engineering Special Issue on "Networked Cooperative Autonomous Systems," 07/2015.
[2] ICRA 2012 Workshop "Crossing the Reality Gap"
[3] ICRA 2013 Workshop "Crossing the Reality Gap"
[4] ICRA 2014 Workshop "Crossing the Reality Gap"
[5] IROS 2014 Workshop on the future of multiple-robot research

Examples (direction to solution)

- 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

Result for Fish & Whales

- 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.

Summary & Conclusion

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

Applicability to General Problem

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- 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)