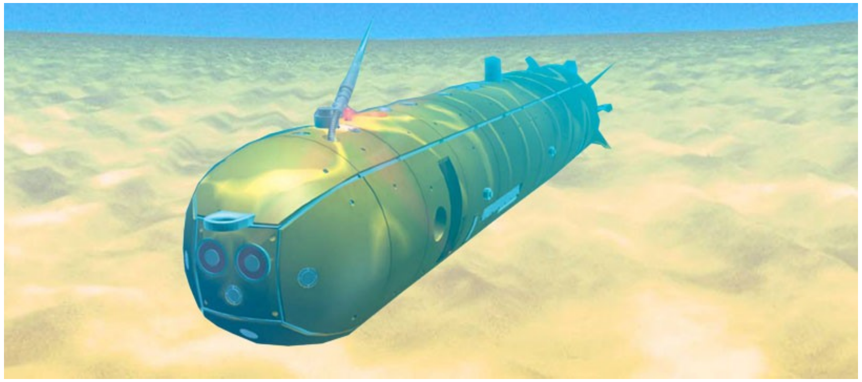
Matrosov Institute for System Dynamics
and Control Theory of Siberian Branch
of Russian Academy of Sciences
(ISDCT SB RAS)

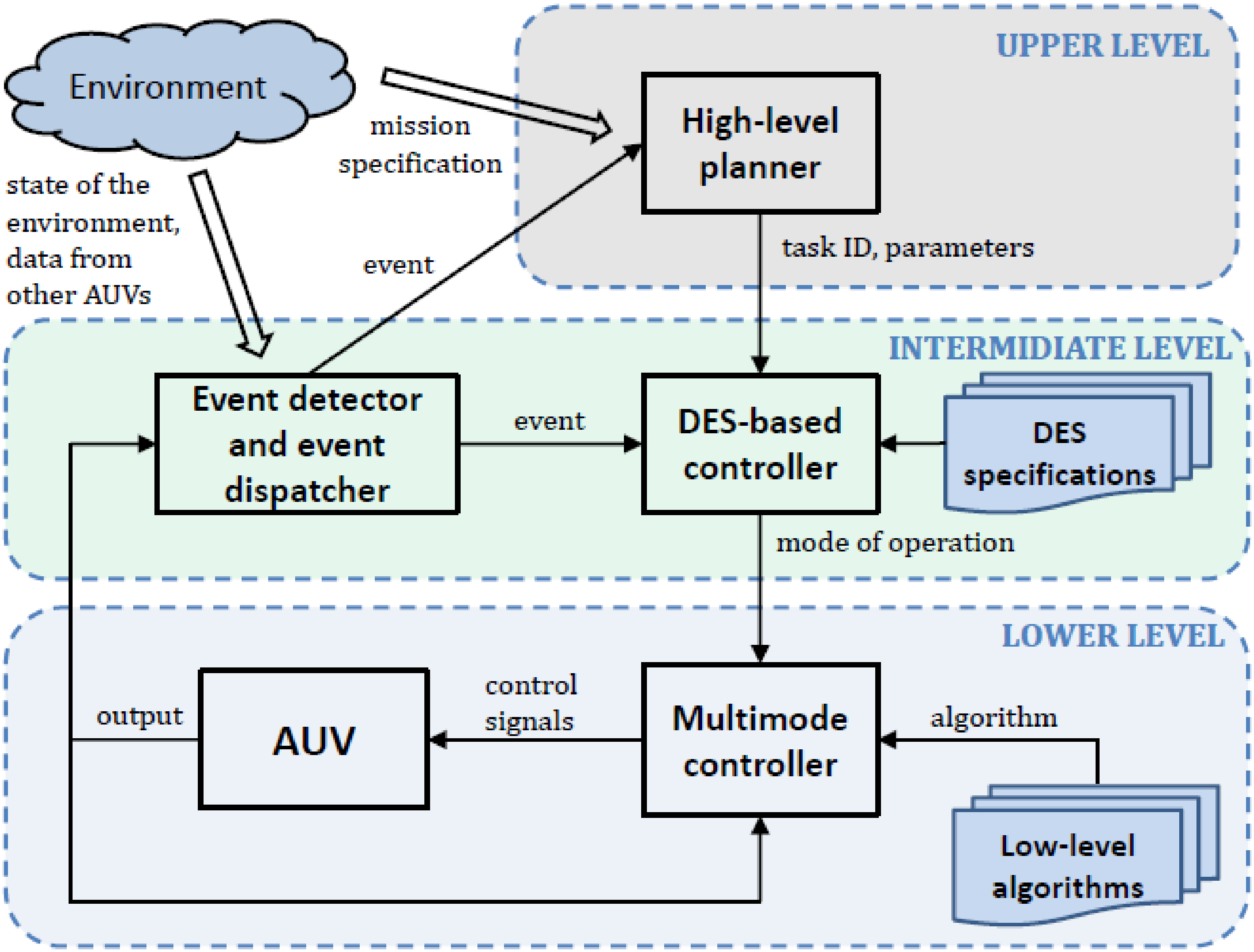
HIERARCHICAL CONTROL SYSTEM DESIGN PROBLEMS FOR MULTIPLE AUTONOMOUS UNDERWATER VEHICLES

Igor Bychkov, Artem Davydov, Maksim Kensin, Nikolay Maksimkin,
Nadezhda Nagul, Ul’yanov Sergey
E-mail: sau@icc.ru



Tomsk, 2019

Hierarchical Control System



Formation Path-Following Control Problem

Leader-follower dynamics:

$$\dot{s}_e = -v_{tl}\cos(\psi_l) + \dot{\psi}_d y_e + v_{tf}\cos(\psi_f)$$

$$\dot{y}_e = -v_{tl}\sin(\psi_l) - \dot{\psi}_d s_e + v_{tf}\sin(\psi_f)$$

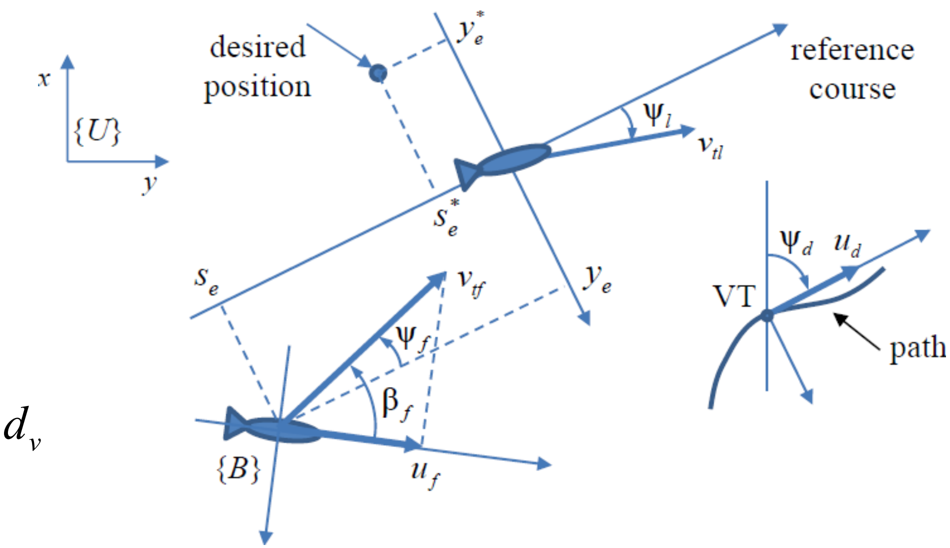
$$\dot{\psi}_f = r_f + \dot{\beta}_f - \dot{\psi}_d$$

AUV dynamics:

$$F \quad = m_u \dot{u} + d_u$$

$$0 \quad = m_v \dot{v} + m_{ur} u r + d_v$$

$$G = m_r \dot{r} + d_r$$



Formation path-following control problem: derive control laws for force F and torque G of each AUV such that

$$\lim_{t\to\infty} | s_e - s_e^* | \le s_e^\infty, \ \lim_{t\to\infty} | y_e - y_e^* | \le y_e^\infty, \quad s_e^\infty \ge 0, \quad y_e^\infty \ge 0$$

s_e^*, y_e^* define a desired position of the follower w.r.t. the leader (or virtual target - VT).

The derived distributed control scheme includes:

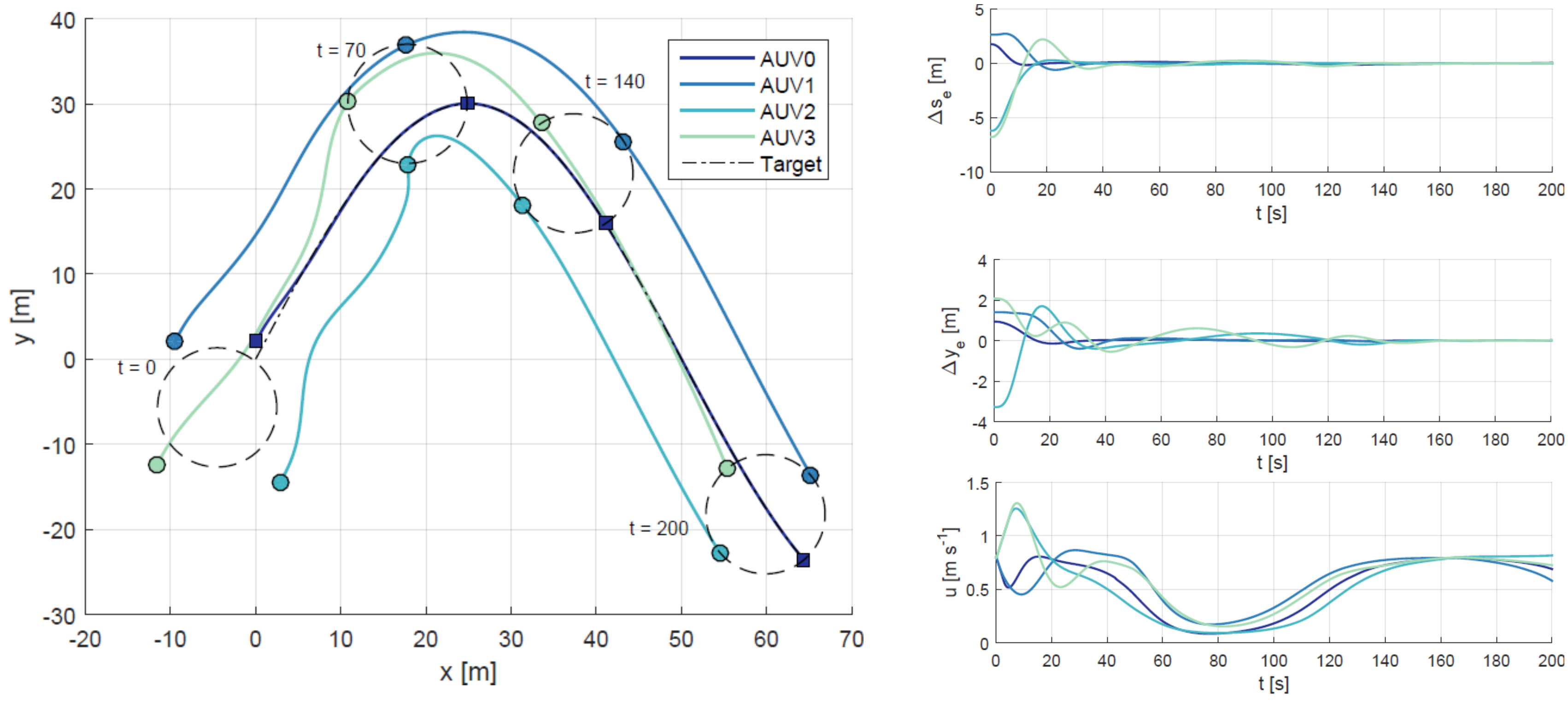
1. Control law for VT that adjusts VT’s travel speed to the irregularities of the path.
2. Sampled-data control algorithm for each AUV to keep its relative position.
3. Simple communication scheme for information exchange between AUVs.

Formation Path-Following Control Problem

Implementation of the control scheme:

1. Gain-scheduled controllers with the path curvature as a scheduling variable.
2. Synthesis of feedback gains for each scheduling region with the use of sublinear vector Lyapunov functions, taking into account: formation structure, communication delays, measurements errors, and control saturation.

Simulation results for underactuated AUVs with $m \approx 2200$ kg, $I_z \approx 2000\,\mathrm{kg} \cdot \mathrm{m}^2$



Analysis of Logical Discrete-Event Systems

Logical DES as a generator of formal language

$$G = \left(Q, \Sigma, \delta, q_0, Q_m\right)$$

Q is the state set;

$\Sigma = \Sigma_c \cup \Sigma_{uc}$ is the set of events, Σ_c is controllable events;

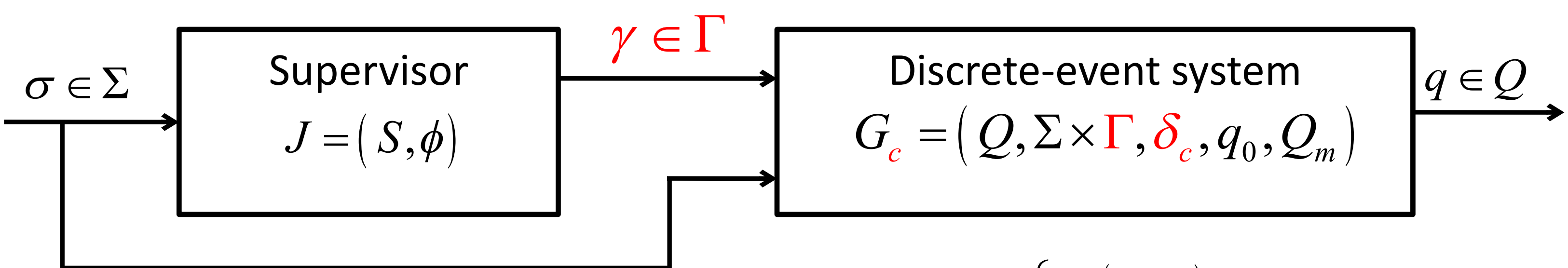
$\delta : \Sigma \times Q \to Q$ is the transition function;

q_0 is the initial state;

$Q_m \subset Q$ is the set of marked states;

Language marked by G: $L_m\left(G\right) \equiv \{w : w \in \Sigma^*$ and $\delta\left(w, q_0\right) \in Q_m$ is defined$\}$

Supervised DES: $J / G \equiv (X \times Q, \Sigma, \xi \times \delta_c, x_0 \times q_0, X_m \times Q_m)$



$$S = \left(X, \Sigma, \xi, x_0, X_m\right)$$

$$\phi : X \to \Gamma \equiv 2^{\Sigma_c}.$$

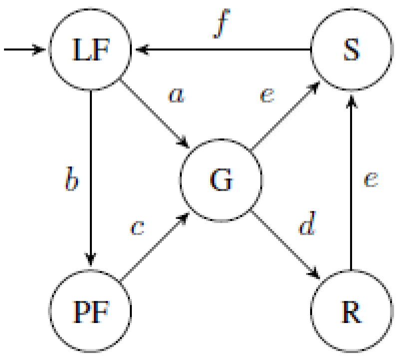
$$\delta_c\left(\gamma, \sigma, q\right) = \begin{cases} \delta\left(\sigma, q\right) & \text{if } \sigma \in \gamma; \\ \text{undefined if } \sigma \notin \gamma. \end{cases}$$

Supervisory control problem:

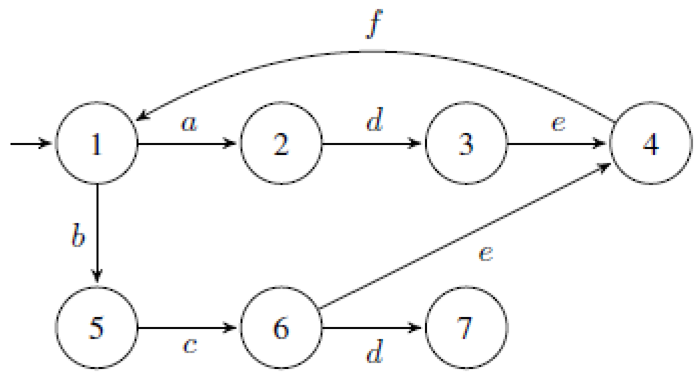
Find J that provide $L_m\left(J / G\right) = K$, K is a specification (language) on DES behavior.

Analysis of Logical Discrete-Event Systems

DES model that describes AUVs modes switching during a survey mission



Generator



Specification

PCF (positively-constructed formulas) inference search using the special developed strategy that gives the answer about the presence of the required property

Formalization of DES in the original first-order language of PCFs

$$B = \{E(a), E(b), E(c), E(d), E(e), E(f), S(p_1(\varepsilon,\varepsilon), LF, 0), S(p_2(\varepsilon,\varepsilon), LF, 0)\}$$

$$\forall \sigma, \sigma', l, E(a), S(p_1(\sigma,\sigma'), LF, l) - \exists S(p_1(\sigma \cdot a, \sigma' \cdot a), G, l+1)$$

$$\forall \sigma, \sigma', l, E(a), S(p_2(\sigma,\sigma'), LF, l) - \exists S(p_1(\sigma \cdot a, \sigma'), G, l+1)$$

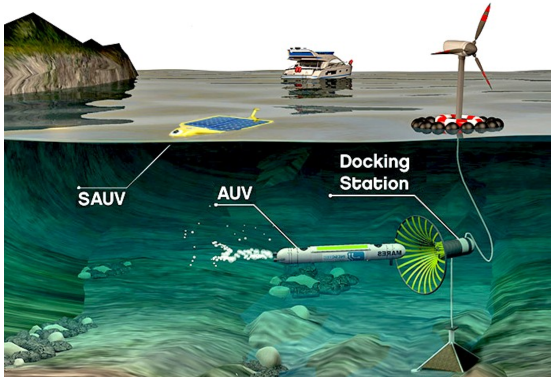
$$\forall \sigma, \sigma', l, E(b), S(p_1(\sigma,\sigma'), LF, l) - \exists S(p_1(\sigma \cdot b, \sigma'), PF, l+1)$$

$$\forall \sigma, \sigma', l, E(b), S(p_1(\sigma,\sigma'), LF, l) - \exists S(p_1(\sigma \cdot b, \sigma' \cdot b), PF, l+1)$$

Coordinated AUVs Group Recharging Scheme

Large-scale monitoring missions of long duration:

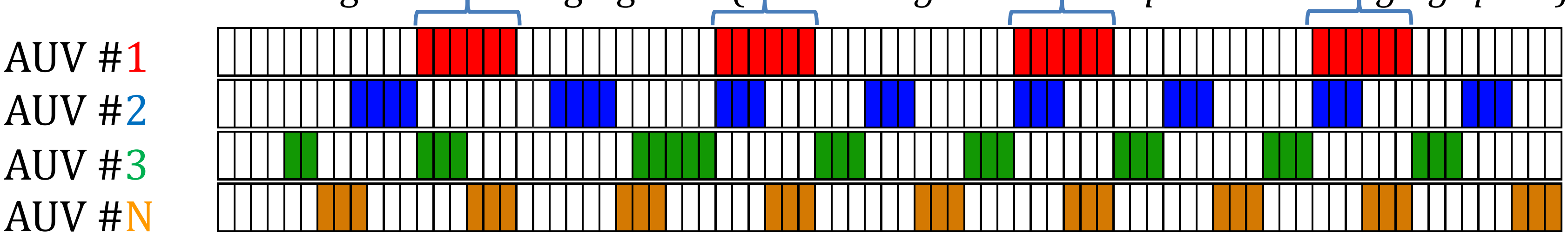
- Vehicles have to *recharge their batteries* periodically;
- Vehicles should *alternate charging cycles* if possible to decrease temporary loss of performance capability;
- Vehicles have to deal with *dynamic mission conditions*.



Discrete representation of the group rotation schedule:

Binary matrix $H = \{h_{ij}\}$ of $N \times e$ size, where $e = \mathrm{T}/\triangle\mathrm{T}$.

Includes traveling time & charging time (*considering both AUV's speed and charging speed*)



– time segment (△T): – vehicle is working; – vehicle is charging (or traveling).

The effectiveness of the group schedule is ensured by:

a. Keeping all vehicles in good working order (well-timed recharging);
b. Excluding simultaneous charging of big number of vehicles (at least, excluding simultaneous charging of the fastest vehicles in the group);
c. Minimizing group rendezvous' frequency where possible.

Coordinated AUVs Group Recharging Scheme

Loss function (1) evaluates the cumulative performance capability of currently charging AUVs on each time segment.

$$f_A(H) = \sum_{i=1}^{e} \left(\left(\sum_{j=1}^{N} \frac{h_{ij}}{N} \right) \left(\sum_{j=1}^{N} \frac{h_{ij} \cdot v^j}{\sum_{j=1}^{N} v^j} \right) \right) \to \min \quad (1)$$

Function (2) estimates the number of expected rendezvous (time intervals, where at least one vehicle changes its status).

$$f_G(H) = \sum_{i=2}^{e} \left(1 - \prod_{j=1}^{N} (1 - |h_{ij} - h_{i-1j}|) \right) \to \min \quad (2)$$

Ultimate schedule efficiency criteria:

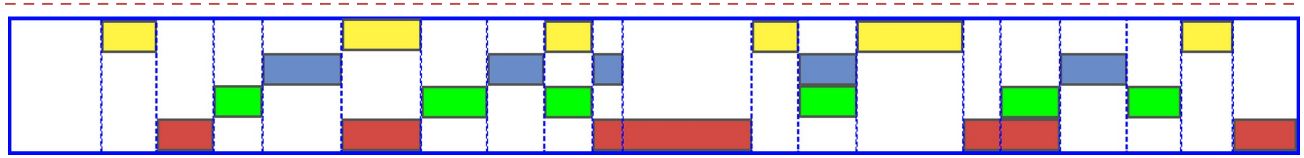
$$f(H) = f_G(H) + f_A(H) \to \min \quad (3)$$

Genetic algorithm – simple, fast and scalable. Allows quick and effective re-planning.

Chromosome (compressed schedule representation to decrease the problem dimension):

Repairing procedure combines solution decoding (into the matrix form) with local optimization.

Group schedule for 4 speed-differed AUVs



AUVs battery level during the mission