Energy-based Control of Multi-Agents System

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[1]Equipe mécatronique et Robotique XLIM / SRI-REMIX

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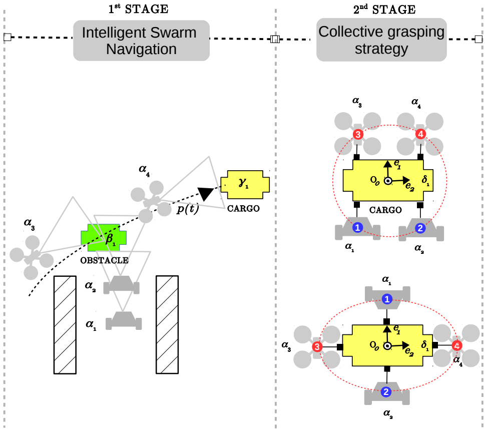
1. Inspired by nature

Nature examples of collective behavior

2. Fundamental questions
   - How do we design flocking/schooling algorithms and guarantee their convergence within an interactive and disturbed context, i.e. degraded feedback information, windy conditions, dynamic obstacles.
   - How do flocks/schools might perform split-rejoin maneuvers (obstacle avoidance, inter-agent collision) using
   - How to adapt/modify/morph the topology, in terms of time-scale the coordination control law based on the per-
   - How to organize the swarm/topology to effectively grasp the payload. Do we split the grasping and detection

Heterogeneous MAS Collective Transport ("Bees + Ants")



- Different motion profile (NH vs H)
- Different time-scale (control and perception)
- Disturbance rejection

Real scenario

$$\dot{x}_i = -\mathrm{sat}\Big(\sum_{j\in\mathcal{N}_i} a_{ij}\big(x(t-\tau_s)_i - x(t-\tau_c)_j\big)\Big) + \Delta(t)_{p_i} + \Delta(t)_{m_i} + \Delta(t)_{e_i} \quad (1)$$

where

τ_s :	Sensors time-delay
τ_s :	Communication time-delay
$\mathrm{sat}(\cdot)$:	Actuators saturation.
$\Delta(t)_p$:	Parametric uncertainties
$\Delta(t)_m$:	Non-linear Nonmodeled terms
$\Delta(t)_e$:	Non-linear External disturbances

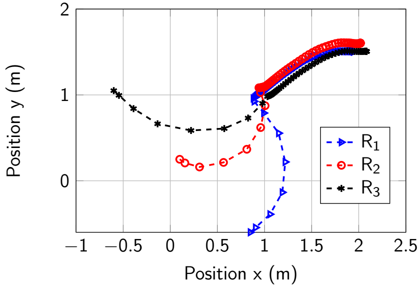


Figure: $3D-$ Region in the $\alpha - \beta$ parameter space, for $\tau \in [0.045, 0.065]$.

Real scenario

$$\dot{x}_i = -\text{sat}\Big(\sum_{j\in\mathcal{N}_i} a_{ij}\big(x(t-\tau_s)_i - x(t-\tau_c)_j\big)\Big) + \Delta(t)_{p_i} + \Delta(t)_{m_i} + \Delta(t)_{e_i} \quad (2)$$

where

- τ_s : Sensors time-delay
- τ_s : Communication time-delay
- $\text{sat}(\cdot)$: Actuators saturation.
- $\Delta(t)_p$: Parametric uncertainties
- $\Delta(t)_m$: Non-linear Nonmodeled terms
- $\Delta(t)_e$: Non-linear External disturbances

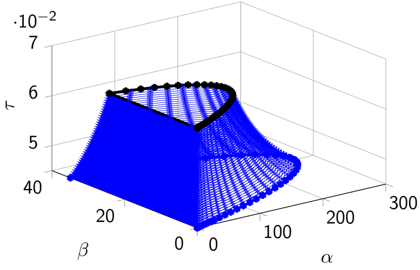


Figure: $3D-$ Region in the $\alpha-\beta$ parameter space, for $\tau \in [0.045, 0.065]$.

Real scenario

$$\dot{x}_i = -\text{sat}\Big(\sum_{j\in\mathcal{N}_i} a_{ij}\big(x(t-\tau_s)_i - x(t-\tau_c)_j\big)\Big) + \Delta(t)_{p_i} + \Delta(t)_{m_i} + \Delta(t)_{e_i} \quad (3)$$

where

τ_s : Sensors time-delay
τ_s : Communication time-delay
$\text{sat}(\cdot)$: Actuators saturation.
$\Delta(t)_p$: Parametric uncertainties
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$\Delta(t)_e$: Non-linear External disturbances

Energy-based Approach: Passivity

- Passivity is intimately to the energy of the system and it provides information about the stability properties [Ortega, et al. Passivity]
- Energy balance:

$$E(t) - E(t_0) = \int_0^T u(t)y(t)d\tau - \int_0^t \dot{q}^T \frac{\partial \mathcal{F}(\dot{q}(t))}{\partial \dot{q}} dt \tag{4}$$

- Why is passivity important?
  - Physical systems it is a restatement of energy conservation.
  - Passivity-based control (PBC) framework fits perfectly to interconnected system
- Applications
  - Mechanical systems
  - Electrical systems
  - Electromechanical system (EL approach OK!)
  - Transportation systems
  - Multi-agent systems (MAS)

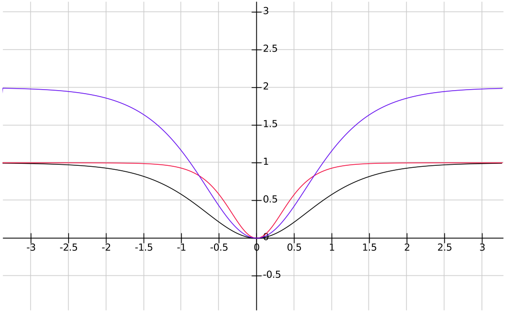
Energy-based Approach: PBC

- Let us consider the multi-agent systems dynamics as

$$m_{(i)}\ddot{q}_{(i)} = U_{(i)} \text{ or } M\ddot{\boldsymbol{q}} = \boldsymbol{U} \tag{5}$$

In this case due to the lack of natural $E_p(t)$, the energy shaping term

$$Ep(t)^d = \frac{1}{2}\mathrm{Tanh}(\tilde{\boldsymbol{q}})^T K_p \mathrm{Tanh}(\tilde{\boldsymbol{q}}) \tag{6}$$

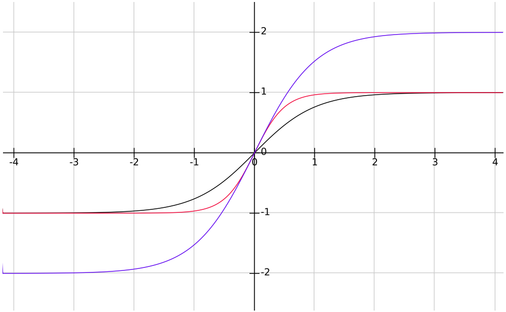


- Hence,

$$\boldsymbol{U}_{ES} = -\frac{\partial Ep(t)^d}{\partial \boldsymbol{q}} = K_p \mathrm{Tanh}(\tilde{\boldsymbol{q}}) \qquad (7)$$

and

$$\boldsymbol{U}_{DI} = -\frac{\partial \mathcal{F}(\dot{\boldsymbol{q}})}{\partial \boldsymbol{q}} = K_d \mathrm{Tanh}(\dot{\boldsymbol{q}}) \qquad (8)$$



- Using $E_p(t)^d$ is now used in the Lyapunov function

$$V = E(t) = \frac{1}{2}\dot{\boldsymbol{q}}^T M \frac{1}{2}\dot{\boldsymbol{q}} + \frac{1}{2}\text{Tanh}(\tilde{\boldsymbol{q}})^T K_p \text{Tanh}(\tilde{\boldsymbol{q}}) \tag{9}$$

whose time dervative

$$\dot{V} = \dot{E}(t) = \dot{\boldsymbol{q}}^T M \ddot{\boldsymbol{q}} + \dot{\boldsymbol{q}}^T \text{Sech}^2(\tilde{\boldsymbol{q}}) K_p \text{Tanh}(\tilde{\boldsymbol{q}}) \tag{10}$$

where considering the following

- $M\ddot{\boldsymbol{q}} = U = U_{ES} + U_{DI}$
- $||\text{Sech}^2(\tilde{\boldsymbol{q}})|| \leq 1$

which yields to

$$\dot{V} = \dot{E}(t) = \dot{\boldsymbol{q}}^T K_d \text{Tanh}(\dot{\boldsymbol{q}}) \tag{11}$$

In order to get into to the MAS form, recall that

- $K_p = \text{diag}(k_{p_1}, \ldots, k_{p_n}$
- $K_d = \text{diag}(k_{d_1}, \ldots, k_{d_n}$
- $\tilde{q}_{(i)} = q_i - q_j$

Thus, the MAS equation is written as

$$\ddot{q}_{(i)} = -k_{p_{(i)}} \tanh(q_{(i)} - q_{(j)}) - k_{d_{(i)}} \tanh(\dot{q}_{(i)}) \tag{12}$$

From the latter, the actual approach fits to the structure of ring topologies.

Concluding Remarks

1. Conclusions
   - The PBC incorporates naturally into the system by dominating the dynamic structure rather than destroying (feedback linearization)
   - The control action is the consequence of a physical (energy) action
   - We come up with an bounded-input regarding the collective MAS behavior based on the artificial potential energy (ES) and the dissipation pattern (DI).
2. Forthcoming research
   - Extend the approach to chain topologies
   - Extend to the trajectory-tracking case
   - Particle model -> fully-actuated rotorcraft
   - Extension to the interactive case via PHCs

Thanks - Q& A