Towards Optimal Information Exchange Instants in Multi-Agent Systems

Domagoj Tolić

University of Dubrovnik & RIT Croatia

Centre de Recherche en Automatique de Nancy (CRAN)
June 26, 2017

Outline

Decentralized Control

- feedback is instrumental for control
- data exchange among neighbors is instrumental in MAS coordination
- data are exchanged intermittently
- realistic communication channels **distort** data, introduce delays and packet dropouts
- however, sensing and broadcasting consume energy

Optimal Decentralized Control

- **quantify** the repercussions of intermittent feedback
- MAS control performance vs. MAS lifetime
- local Dynamic Programming (DP) problems are coupled $\implies$ nonautonomous dynamics $\implies$ non-stationary cost-to-go
- the need for an online model-free Reinforcement Learning (RL) method
- Kalman Filtering (KF) for delayed, sampled and noisy data

Impulsive delayed systems

$$\Sigma \begin{cases} \dot{x}(t) = Ax(t) + A_d x(t-d) + B\omega(t), & t \notin \mathcal{T}, \\ y(t) = Cx(t) + C_d x(t-d) + D\omega(t), & t \geq t_0, \\ x(t^+) = Ex(t) + E_d x(t-d), & t \in \mathcal{T}, \end{cases}$$

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where $x \in \mathbb{R}^{n_x}$ is the state, $\omega \in \mathbb{R}^{n_\omega}$ is the input, $y \in \mathbb{R}^{n_y}$ is the output and $d \geq 0$ is the time delay

$\mathcal{L}_p$-stability w.r.t. Set and with Bias

- $\mathcal{L}_p$-norm w.r.t. a set $\mathcal{B} \subset \mathbb{R}^n$:
  $\|f[a,b]\|_{p,\mathcal{B}} := \left(\int_{[a,b]} \|f(s)\|_{\mathcal{B}}^p \mathrm{d}s\right)^{1/p}$, where
  $\|f(s)\|_{\mathcal{B}} := \inf_{b\in\mathcal{B}} \|f(s) - b\|$ and $p \in [1,\infty]$
- output set:
  $\mathcal{B}_y := \left\{y \in \mathbb{R}^{n_y} | \exists b \in \mathcal{B} \text{ such that } y = (C + C_d)b\right\}$, where
  $\mathcal{B} := \mathrm{Ker}(A + A_d)$

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Definition ($\mathcal{L}_p$-Stability w.r.t. $\mathcal{B}$ with Bias b)

Let $p \in [1, \infty]$. The system Σ is $\mathcal{L}_p$-stable w.r.t. a set $\mathcal{B}$ and with bias $b(t) \equiv b \geq 0$ from ω to y with gain $\gamma \geq 0$ if there exists $K \geq 0$ such that, for each $t_0 \in \mathbb{R}$ and each $\psi_x \in PC([t_0 - d, t_0], \mathbb{R}^{n_x})$, each solution to Σ from ψ_x at $t = t_0$ satisfies
$\|y[t_0, t]\|_{p,\mathcal{B}_y} \leq K \|\psi_x\|_{d,\mathcal{B}} + \gamma \|\omega[t_0, t]\|_p + \|b[t_0, t]\|_p$ for each $t \geq t_0$.

Agent Dynamics

- consider N heterogeneous linear agents given by

$$\dot{\xi}_i = A_i\xi_i + B_i u_i + \omega_i,$$
$$\zeta_i = C_i\xi_i, \qquad (1)$$

where $\xi_i \in \mathbb{R}^{n_{\xi_i}}$ is the state, $u_i \in \mathbb{R}^{n_{u_i}}$ is the input, $\zeta_i \in \mathbb{R}^{n_\zeta}$ is the output of the i^{th} agent, $i \in \{1, 2, \ldots, N\}$, and $\omega_i \in \mathbb{R}^{n_{\xi_i}}$ reflects exogenous disturbances and/or modeling uncertainties

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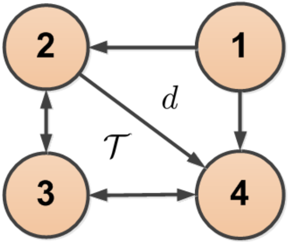
- a common decentralized policy is

$$u_i(t) = -K_i \sum_{j \in \mathcal{N}_i} (\zeta_i(t) - \zeta_j(t)), \tag{2}$$

where K_i is an $n_{u_i} \times n_\zeta$ gain matrix

Agent Interconnections



Closed-Loop Dynamics

- define $\xi := (\xi_1, \ldots, \xi_N)$, $\zeta := (\zeta_1, \ldots, \zeta_N)$ and $\omega := (\omega_1, \ldots, \omega_N)$
- utilizing the Laplacian matrix L of the communication graph $\mathcal{G}$, we reach

$$\begin{aligned} \dot{\xi}(t) &= A^{\mathrm{cl}}\xi(t) + A^{\mathrm{cld}}\xi(t-d) + \omega(t), \\ \zeta &= C^{\mathrm{cl}}\xi, \end{aligned}$$

with

$$\begin{aligned} A^{\mathrm{cl}} &= \mathrm{diag}(A_1, \ldots, A_N), & A^{\mathrm{cld}} &= [A_{ij}^{\mathrm{cld}}], \\ A_{ij}^{\mathrm{cld}} &= -l_{ij}B_iK_iC_j, & C^{\mathrm{cl}} &= \mathrm{diag}(C_1, \ldots, C_N), \end{aligned}$$

Optimal Intermittent Feedback

- $t_i^j \in \mathcal{T}$, $i \in \mathbb{N}$ – broadcasting instants of the j^{th} agent
- asynchronous communication
- $x_i := (\ldots, \zeta_i - \zeta_j, \ldots)$, where $i \in \{1, \ldots, N\}$ and $j \in \mathcal{N}_i$

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Problem

For each $j \in \{1, \ldots, N\}$, minimize the following cost function that captures performance vs. energy trade-offs

$$\mathop{\mathbb{E}}_{\omega}\left\{ \sum_{i=1}^{\infty} (\gamma_j)^i \underbrace{\left[\int_{t_{i-1}^j}^{t_i^j} (x_j^\top P_j x_j + u_j^\top R_j u_j)\mathrm{d}t + S_j \right]}_{r_j(x_j, u_j, \tau_i^j)} \right\} \quad (3)$$

for the j^{th} agent of MAS (1)-(2) over all sampling policies τ_i^j and for all initial conditions $x_j(t_0) \in \mathbb{R}^{n_{x_j}}$.

Interconnecting Nominal and Error System

- introduce

$$e(t) = (e_1(t), \dots, e_N(t)) := \hat{\zeta}(t) - \zeta(t-d)$$

- closed-loop dynamics become

$$\dot{\xi}(t) = A^{\text{cl}}\xi(t) + A^{\text{cld}}\xi(t-d) + A^{\text{cle}}e(t) + \omega(t),$$
$$\zeta = C^{\text{cl}}\xi,$$

with $A^{\text{cle}} = [A_{ij}^{\text{cle}}]$, $A_{ij}^{\text{cle}} = -l_{ij}B_iK_i$

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- ZOH sampling yields

$$\dot{e}(t) = -\dot{\zeta}(t-d) = -C^{\text{cl}}\dot{\xi}(t-d),$$

- for each $t_i^j + d \in (\mathcal{T} + d)$ we have

$$e_k((t_i^j + d)^+) = e_k(t_i^j + d), \qquad k \in \{1, \ldots, N\}, k \neq j,$$
$$e_j((t_i^j + d)^+) = \nu_j(t_i^j + d)$$

Small-Gain Theorem

- select

$$\tilde{\zeta} := -C^{\mathrm{cl}}\left[A^{\mathrm{cl}}\xi(t-d) + A^{\mathrm{cld}}\xi(t-2d) + \omega(t-d)\right]$$

to be the output of the nominal system for which

$$\|\tilde{\zeta}[t_0,t]\|_{p,\mathcal{B}_{\tilde{\zeta}}} \leq K_n\|\psi_\xi\|_{d,\mathcal{B}} + \gamma_n\|(e,\omega)[t_0,t]\|_p \qquad (4)$$

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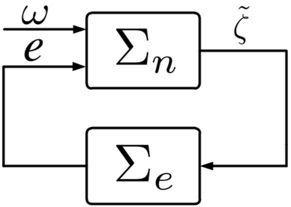

Stabilizing Broadcasting Intervals

Theorem

Suppose the communication link delay d for the MAS (1)-(2) yields (4) for some $p \in [1, \infty]$. If the broadcasting intervals τ_i^j, $i \in \mathbb{N}$, $j \in \{1, \dots, N\}$, satisfy (I) and (II) for some $\lambda > 0$ and $M > 1$ such that $\frac{2}{\lambda}\sqrt{M}\gamma_n < 1$, then the MAS (1)-(2) is $\mathcal{L}_p$-stable from ω to $(\tilde{\zeta}, e)$ w.r.t. $(\mathcal{B}, \mathbf{0}_{n_e})$ and with bias.

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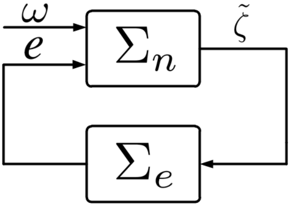
- we can always choose τ_i^j's such that
  - (I) $\tau_i^j\left(\lambda + r + \lambda_1 M e^{-\lambda \tau_i^j}\right) < \ln M$, and
  - (II) $\tau_i^j\left(\lambda + r + \frac{\lambda_1}{\lambda_2} e^{\lambda d}\right) < -\ln \lambda_2$,

  with $r > 0$ being an arbitrary constant, $\lambda_1 := \frac{N\|C^{\mathrm{cl}} A^{\mathrm{cle}}\|^2}{r}$ and $\lambda_2 := \frac{N-1}{N}$.

Stabilizing Broadcasting Intervals

Corollary

Suppose the conditions of the theorem hold and ξ is $\mathcal{L}_p$-detectable from $(e, \omega, \tilde{\zeta})$ w.r.t. $\mathcal{B}$. Then the MAS (1)-(2) is $\mathcal{L}_p$-stable with bias w.r.t. $(\mathcal{B}, \mathbf{0}_{n_e})$ from ω to (ξ, e).



Experimental Results

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Least Square Policy Iteration (LSPI) I

- LSPI state-action approximate value function is

$$\hat{Q}(x(t_i), \tau(t_i)) = \Phi^\top\big(x(t_i), \tau(t_i)\big)\alpha_\kappa, \tag{5}$$

where

$$\Phi\big(x(t_i), \tau(t_i)\big) = \psi(\tau(t_i)) \otimes \phi(x(t_i))$$

is the Kronecker product of the basis function vectors $\psi(\tau(t_i))$ and $\phi(x(t_i))$ formed with Chebyshev polynomials while α_κ is **being learned**

Least Square Policy Iteration (LSPI) II

- define $\tau(t_i) := t_{i+1} - t_i$
- decision $\tau(t_i) \in \mathcal{A}$ is given by

$$\tau(t_i) = h_\kappa\big(x(t_i)\big),$$

where

$$h_\kappa\big(x(t_i)\big) = \begin{cases} \text{u.r.a.} \in \mathcal{A} & \text{every } \varepsilon \text{ iterations,} \\ h_\kappa\big(x(t_i)\big) & \text{otherwise,} \end{cases}$$

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where “u.r.a." stands for “uniformly chosen random action" and yields exploration every ε steps while $h_\kappa(x(t_i))$ is the policy obtained according to

$$h_\kappa(x(t_i)) \in \arg\min_u \hat{Q}\big(x(t_i), \tau(t_i)\big) \qquad (6)$$

Least Square Policy Iteration (LSPI) III

- α_κ is updated every $\kappa \geq 1$ steps from the projected Bellman equation for model-free policy iteration

$$\Gamma_i \alpha_\kappa = \gamma \Lambda_i \alpha_\kappa + z_i,$$

where γ is from (3) and

$$\Gamma_0 = \beta_\Gamma \boldsymbol{I}, \quad \Lambda_0 = \mathbf{0}, \quad z_0 = \mathbf{0},$$
$$\Gamma_i = \Gamma_{i-1} + \phi\big(x(t_i), \tau(t_i)\big)\phi\big(x(t_{i-1}), \tau(t_{i-1})\big)^\top,$$
$$\Lambda_i = \Lambda_{i-1} + \phi\big(x(t_i), \tau(t_i)\big)\phi\big(x(t_i), h(x(t_{i+1}))\big)^\top,$$
$$z_i = z_{i-1} + \phi\big(x(t_i), \tau(t_i)\big)r(t_i),$$

where Γ_i, Λ_i and z_i are updated at every iteration step i

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- new α_κ improves the Q-function (5)
- improved policies (in the sense of Problem) are obtained from (6)

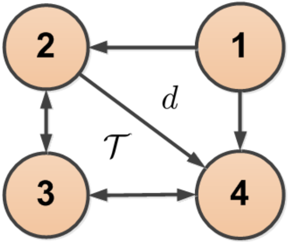
AR.Drone Parrot Quadcopter Identification

- a group of four agents with identical dynamics

$$\dot{\xi}_i = \begin{bmatrix} 0 & 1 \\ 0 & -T_p \end{bmatrix} \xi_i + \begin{bmatrix} 0 \\ K_p \end{bmatrix} u_i + \omega_i,$$
$$\zeta_i = \begin{bmatrix} 0.05 & 0.025 \end{bmatrix} \xi_i,$$

where $K_p = 5.2$ and $T_p = 0.38$

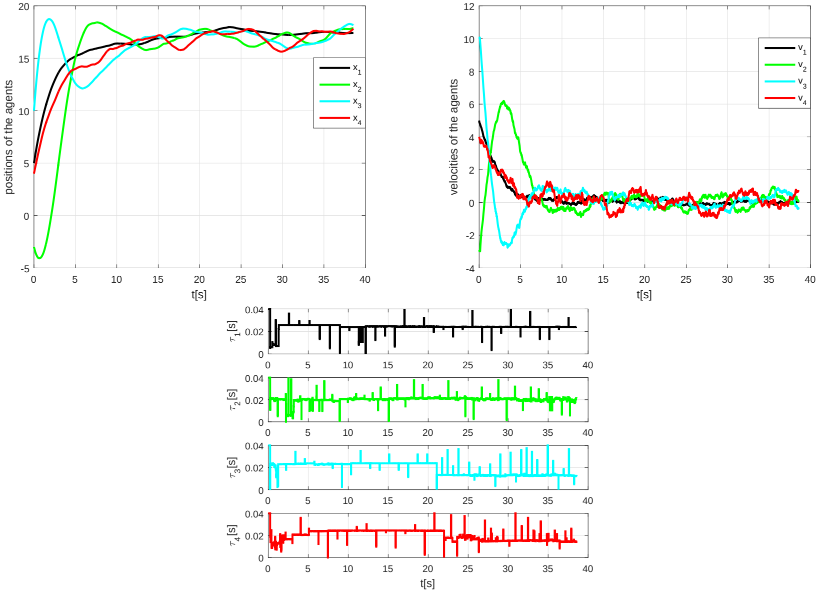
- communication delay is $d = 0.104$ s



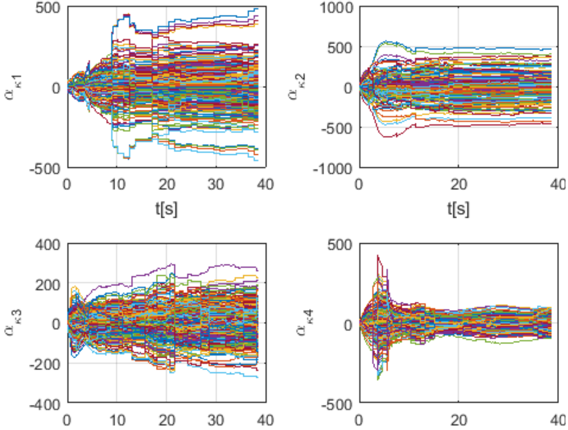
Simulation Parameters

- select $K_1 = \ldots = K_4 = 0.5$ in (2)
- $\tau_i^j \in \mathcal{A} := [\underline{\tau}, \overline{\tau}]$
- the theorem yields $\overline{\tau} = 0.04$ s, while we choose $\underline{\tau} = 10^{-5}$ s
- tuning parameters for LSPI are: $\kappa = 2$ and $\varepsilon = 50$
- we choose $\mathcal{X} = [-30, 30]$
- cost function parameters: $\gamma_1 = \ldots = \gamma_4 = 0.99$, $P_2 = P_3 = 5I_2$, $P_4 = 5I_3$, $R_1 = \ldots = R_4 = 5$ and $S_1 = \ldots = S_4 = 20$

Numeric Results I



Numeric Results II



Concluding Remarks

- optimal intermittent feedback problem in MASs
- a goal function that captures local MAS performance vs. agent lifetime trade-offs
- **first**, compute provably stabilizing upper-bounds on agents' broadcasting intervals
- **second**, bring together estimation (KF) and an online model-free LSPI method to tackle coupled partially observable DP problems
- directed and unbalanced communication topologies
- large delays

Thanks

This work has been supported in part by Croatian Science Foundation under the project IP-2016-06-2468 “ConDyS” and by NATO under the grant SfP - 984807 - MORUS - “Unmanned System for Maritime Security and Environmental Monitoring”.

ConDyS

MORUS

Questions? Comments? Suggestions?

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Thank You for Your attention!!