Collective Decision-Making and Control in Heterogeneous Multi-agent Systems

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July 12, 2020
Workshop on Heterogeneous Multi-Robot Task Allocation and Coordination
Robotics: Science and Systems, 2020
[Virtual Event]

Bio-Inspired Decision-Making and Control in Heterogeneous Multi-agent Systems

Collective Decision-Making in Honeybees Nest-Site Selection

Scouts apply “stop signal” with head butt to dancers for alternative sites.


Collective Decision-Making in Animal Groups on the Move

Towards a Generalized Model of Collective Decision-Making

- How to design distributed algorithms that exhibit such rich behavior in multi-agent systems
- What is the influence of heterogeneity on system behavior?
Can Consensus Dynamics Achieve Collective Decisions?

- Agent state: $x_i(t) \in \mathbb{R}, \quad i = 1, \ldots, N$
  
  $x_i(t) > 0$ for alternative A
  
  $x_i(t) = 0$ uncommitted
  
  $x_i(t) < 0$ for alternative B

- Continuous time consensus seeking in a social network

$$\dot{x}_i(t) = \sum_{j=1}^{N} a_{ij}(x_j - x_i) = -d_i x_i + \sum_{j=1}^{N} a_{ij} x_j$$

- For same number agents favoring each alternative, steady state is zero

- Averaging-based consensus can lead to deadlock, i.e., no nest selection

The Key Insight: Pitchfork Bifurcation and Agreement by Design

$$\dot{x} = F(x, u, \beta) = \beta - Dx + uAS(x)$$

- For $\beta = 0$ and $u = 1$, the linearized dynamics admits a center manifold

- The center manifold is tangent to consensus manifold

- Under appropriate conditions, it can be shown that trajectories always enter center manifold

- The dynamics on center manifold is designed to admit pitchfork bifurcation

- Pitchfork bifurcations occur under $S_2$ symmetry

- Heterogeneity breaks symmetry

A Generalized Model

- Negative self feedback

- Positive social feedback

$$x_i = \beta_i - d_i x_i + \sum_{j=1}^{N} u a_{ij} s(x_j)$$

- $u > 0$ social effort

Interplay of Heterogeneities in the Abstract Model

- Two trackable schemes

  - Deterministic nonlinear setting ($\Sigma = 0$)

  - Linear Stochastic Setting ($S(x) = x$)

- Many interesting questions

  - Selecting leader agents

  - Influence of heterogeneity of information, correlation, and location on performance
Robustness of Pitchfork Singularity to Heterogeneity

- The perturbation of pitchfork singularity can lead to one of the four bifurcation diagrams.
- The qualitative behavior of the equilibrium points remains the same.
- Pitchfork singularity provide the flexibility to address conflicts due to heterogeneity, while ensuring robustness of resulting behavior.

Group State: $y(t) = \sum_{i=1}^{N} x_i(t)$

Value-Sensitive Decision-Making

Can we recover value-sensitive decision-making observed in honeybees?

Adaptive Control of Bifurcation Parameters

Can we adapt bifurcation parameter distributedly to achieve desired collective behavior?

Conclusions

- Heterogeneity offers resilient behavior but can lead to decision deadlocks
- Natural systems exhibit rich behavior that balances flexibility and robustness
- Singularity theory and bifurcation analysis offers a formal mathematical framework to study such flexible and robust behavior
- Proposed a general model that achieves such behavior in multi-agent systems
- Influence of heterogeneity in this model

Acknowledgements

Naomi Leonard
Alessio Franci
Rebecca Gray

Thank you!

Questions?