Biomimetic Algorithms for Coordinated Motion: Theory and Implementation

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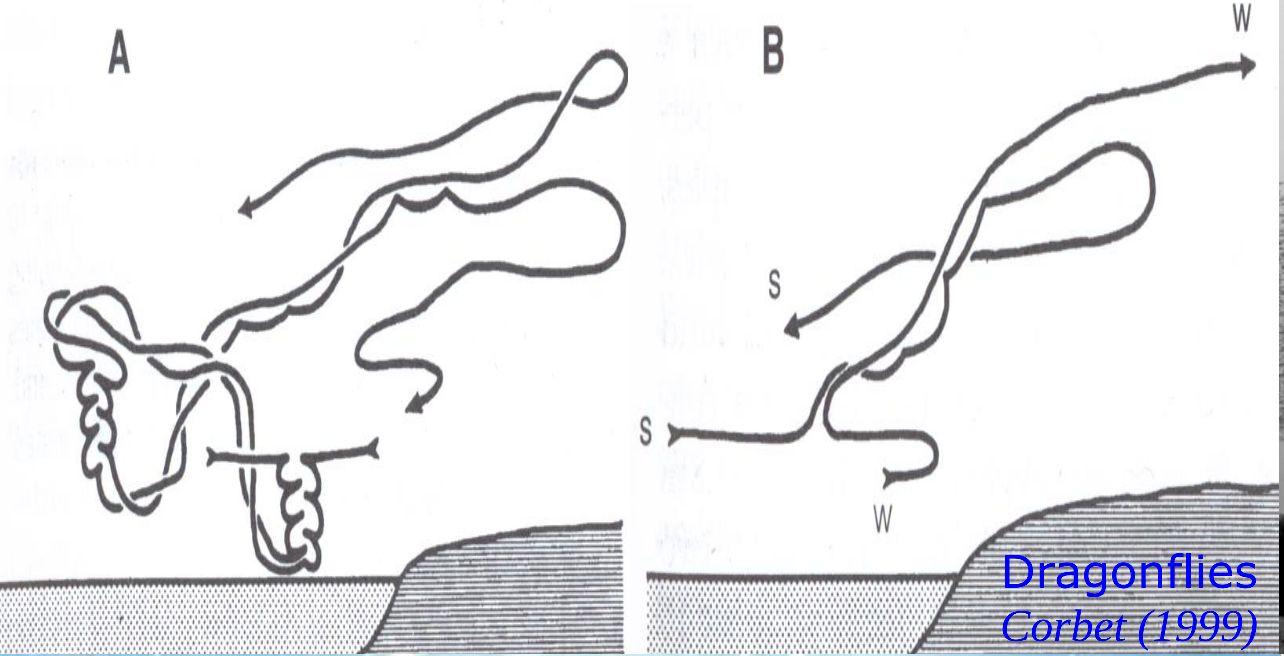
Background and Motivation



Dragonflies
Corbet (1999)


Starling Flock
evolvingbliss.com


Fish School
Huffington Post


Wildebeest
tanzaniaonfoot.com

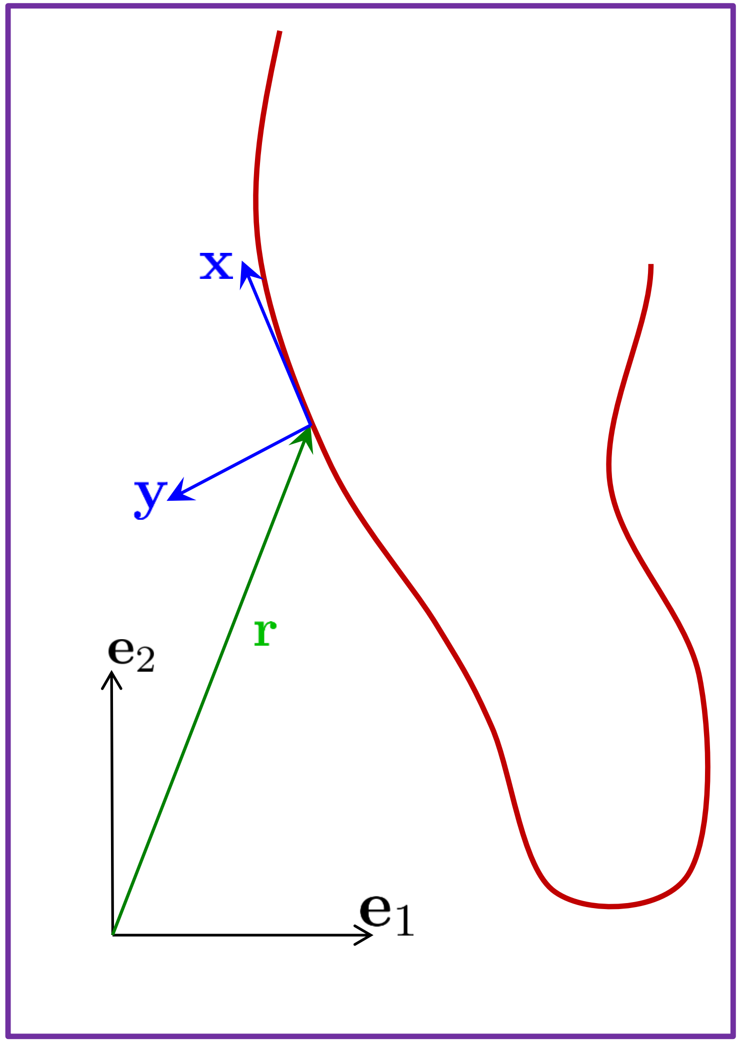
Self-steering Particle Model

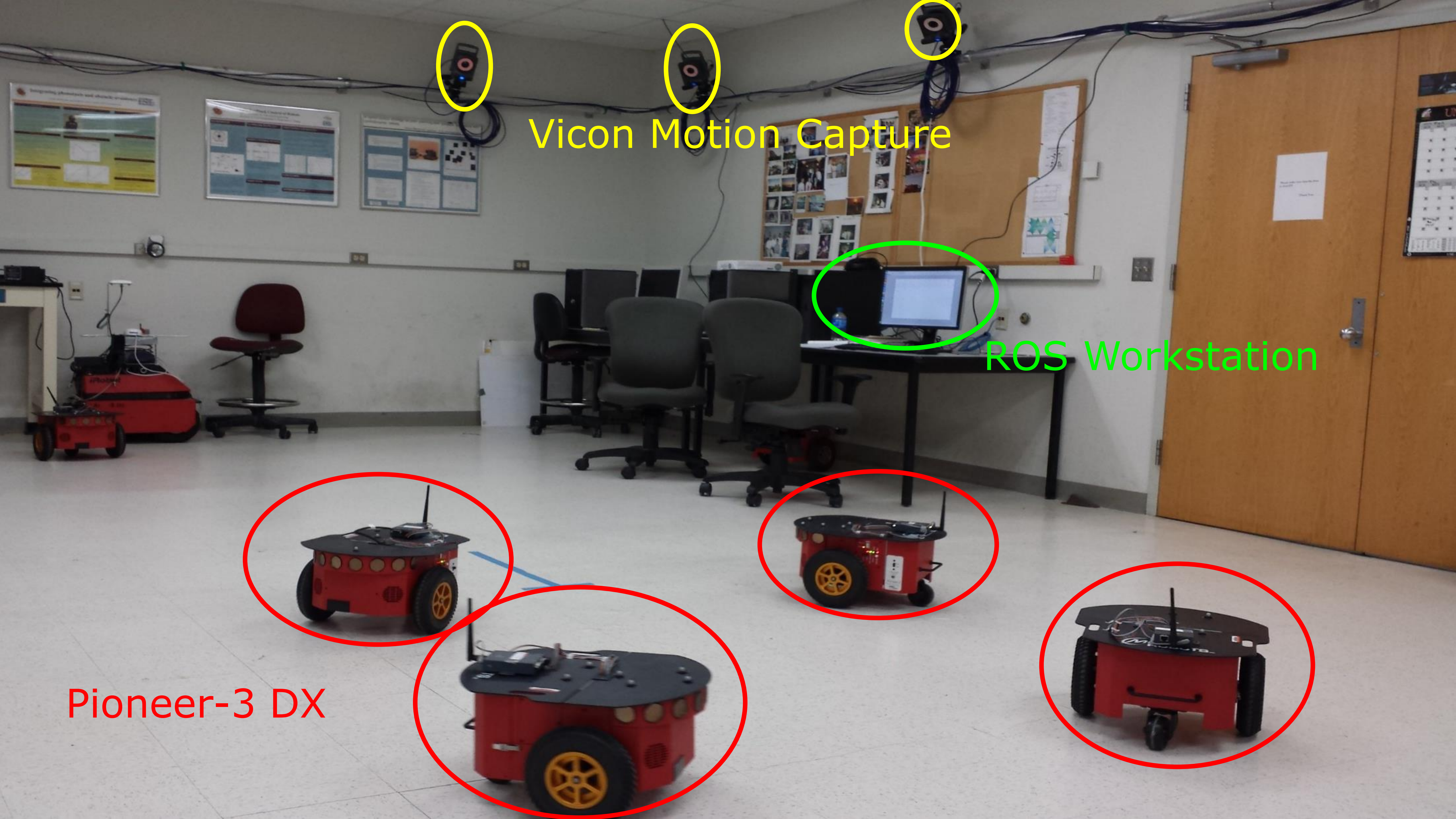
- Position vector: $\mathbf{r}$
- Normalized velocity: $\mathbf{x} = \dfrac{\dot{\mathbf{r}}}{|\dot{\mathbf{r}}|}$
- Unit vector perpendicular to normalized velocity: $\mathbf{y}$

- Speed: $\nu = |\dot{\mathbf{r}}|$
- Steering Control: u

- Dynamics of i -th agent:

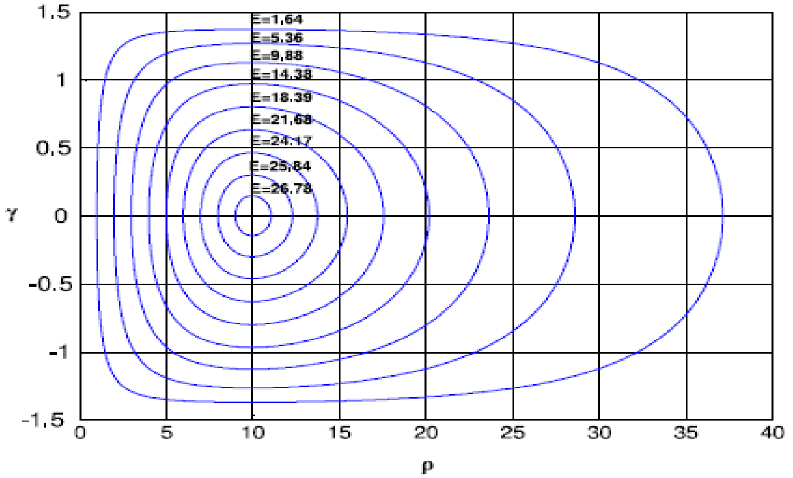
$$\begin{aligned} \dot{\mathbf{r}}_i &= \nu_i \mathbf{x}_i \\ \dot{\mathbf{x}}_i &= \nu_i u_i \mathbf{y}_i \\ \dot{\mathbf{y}}_i &= -\nu_i u_i \mathbf{x}_i \end{aligned}$$




Vicon Motion Capture
ROS Workstation
Pioneer-3 DX

Mutual Motion Camouflage (MMC)

- Inspiration: Dragonfly foraging and territorial battles
- 2 agents, pursuing each other
- Feedback control law*: $\boxed{u = -\mu\lambda}$ $\quad \mu > 0, \quad \lambda = \dfrac{\mathbf{r}_{12} \cdot \dot{\mathbf{r}}_{12}^{\perp}}{|\mathbf{r}_{12}|}$
- Reduced dynamics: $$\boxed{\begin{aligned} \dot{\rho} &= \gamma \\ \dot{\gamma} &= (1/\rho - \mu)\left(\delta^2 - \gamma^2\right) \end{aligned}}$$ $\rho = |\mathbf{r}_{12}|, \quad \gamma = \dfrac{\mathbf{r}_{12} \cdot \dot{\mathbf{r}}_{12}}{|\mathbf{r}_{12}|},$
- $\boxed{E(\rho, \gamma) = \rho^2(\delta^2 - \gamma^2)e^{-2\mu\rho} = \text{Conserved Quantity!}}$



Phase portrait of the reduced dynamics*

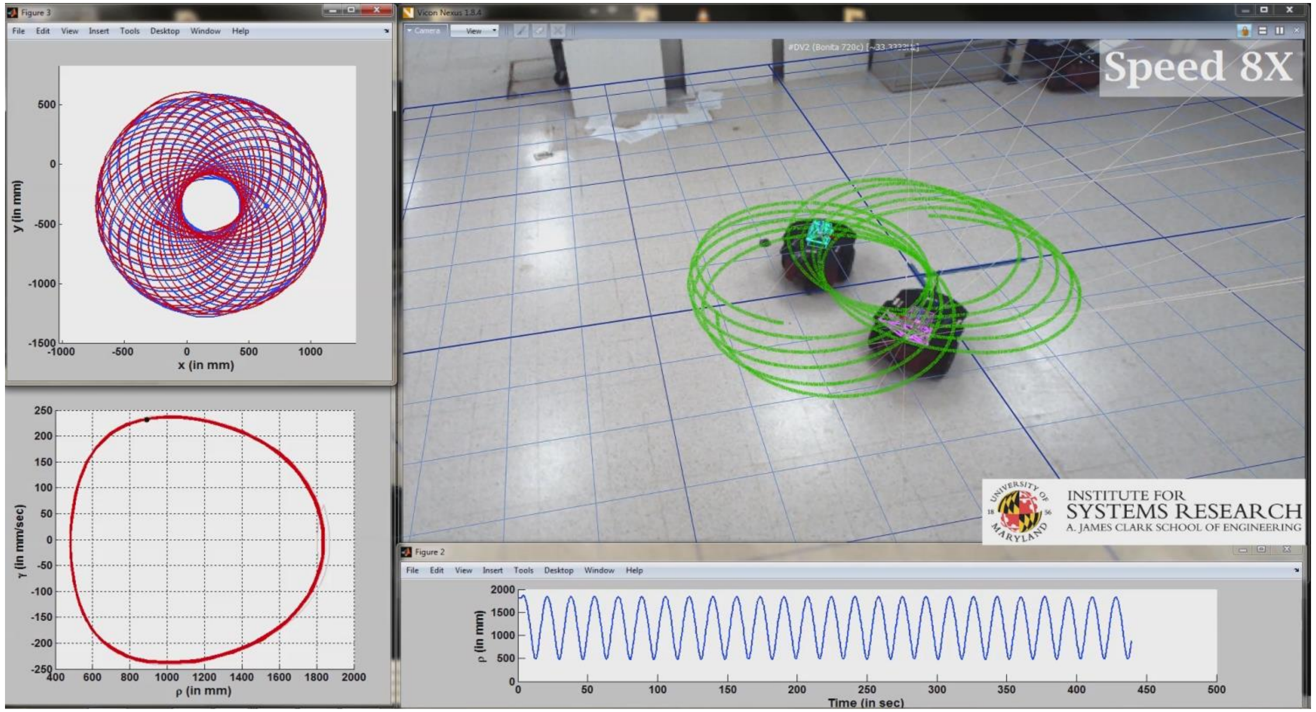
*M. Mischiati and P. S. Krishnaprasad, "The dynamics of mutual motion camouflage," Systems & Control Letters, 61(9):894–903, 2012.

Mutual Motion Camouflage (MMC)

- Problem: Small perturbations were drifting the system away from the desired orbit.
- Solution: Introduction of Dissipation.
- Modified feedback control law: $\boxed{u = -\mu\lambda + k_d \lambda \gamma \big(E(\rho, \gamma) - E_d\big)}$

$$k_d > 0$$
$$E_d = E(\rho_0, \gamma_0)$$

- Result:



http://ter.ps/ICRA205

Topological Velocity Alignment (TVA)

- **Inspiration:** Starling murmuration
- Each of N-agents pays attention to its k-nearest neighbors.

- Velocity of Neighborhood Center of Mass: $$\mathbf{v}_{COM} = \frac{1}{|\mathcal{N}_i|}\sum_{j\in\mathcal{N}_i} \nu_j \mathbf{x}_j$$

  $\mathcal{N}_i$: neighborhood of the i-th agent

- Direction of motion of the neighborhood center of mass: $$\mathbf{x}_{\mathcal{N}_i} = \frac{\mathbf{v}_{COM}}{|\mathbf{v}_{COM}|}$$ if $\mathbf{v}_{COM} \neq \mathbf{0}$

- **Contrast Function***:

$$\Theta_i = \frac{1}{2}\left(\mathbf{x}_{\mathcal{N}_i} - \mathbf{x}_i\right)\cdot\left(\mathbf{x}_{\mathcal{N}_i} - \mathbf{x}_i\right)$$

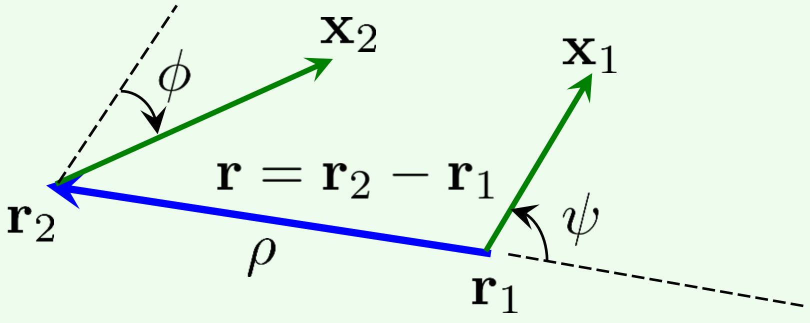
$$\Theta_{total} = \sum_{i=1}^{n} \Theta_i$$

*B. Dey, "Reconstruction, Analysis and Synthesis of Collective Motion", PhD Thesis, University of Maryland, College Park, Feb 2015.

Topological Velocity Alignment (TVA)

- Feedback Control Law: $$\boxed{u_i = \left(\frac{\mu}{\nu_i}\right)\left[\mathbf{x}_{\mathcal{N}_i} \cdot \mathbf{y}_i\right]}$$ $\mu > 0$

Special Case: 2-agent System



- Closed Loop Shape Dynamics:

$$\dot{\rho} = \nu_1 \cos\psi - \nu_2 \cos(\psi - \phi)$$

$$\dot{\psi} = -\mu \sin\phi - \frac{1}{\rho}\left[\nu_1 \sin\psi - \nu_2 \sin(\psi - \phi)\right]$$

$$\dot{\phi} = -2\mu \sin\phi$$

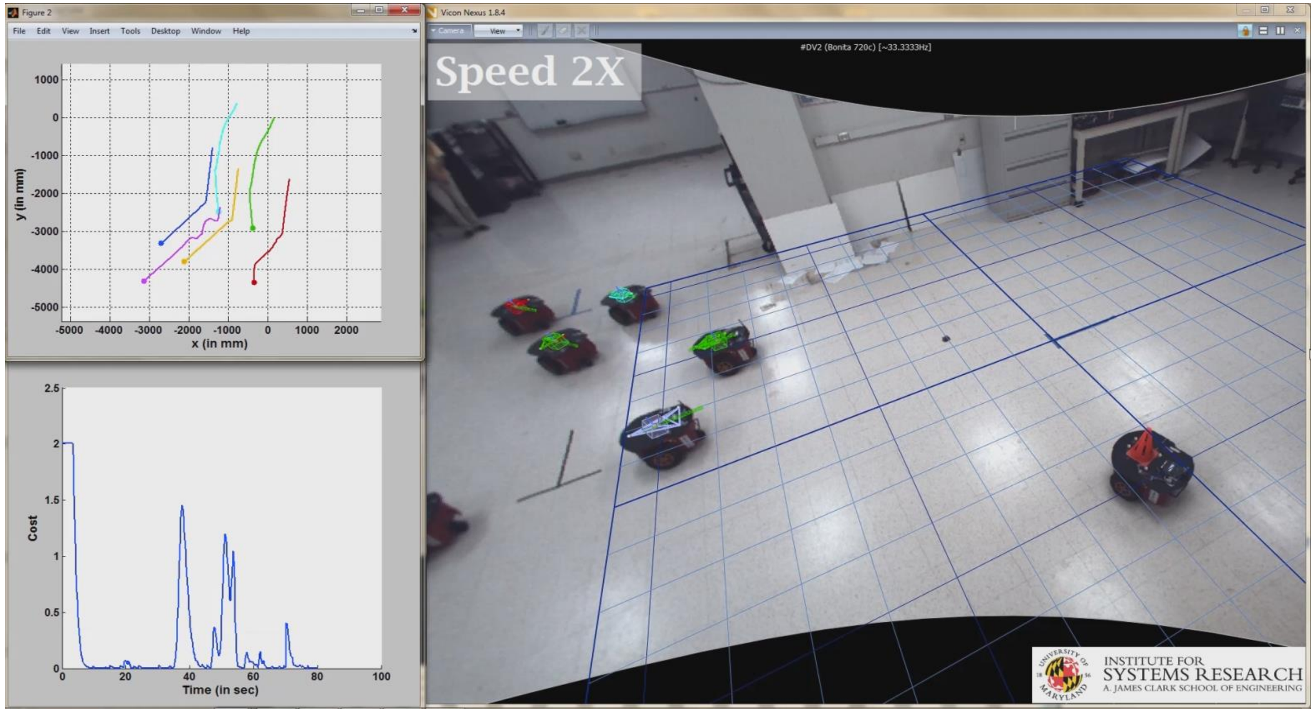
- Contrast Function: $\Theta = 1 - \cos\phi$

Theorem:

If $\Theta(0) \neq 2$, i.e. if the agents are not heading directly away from each other initially, then $\Theta(t)$ converges to zero asymptotically.

Topological Velocity Alignment (TVA)

- ❑ Problem: Direction of motion becomes undefined whenever the neighbourhood center of mass velocity vanishes to zero.
- ❑ Solution:
  - ❑ A heuristic approach to tackle this singularity.
  - ❑ This is done by appending another agent into the neighborhood of the focal agent whenever the velocity of its neighborhood center of mass vanishes.
- ❑ Result:



http://ter.ps/ICRA205

Future Directions

- Effect of a beacon (influencing both agents) into MMC.
- Equip a single agent with extra information about the environment and understand its effect on the entire swarm.
- Study the effect of sensor noise and perform robustness analysis.

Thank you!