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Collaborative autonomous agents: state-of-the-art and research challenges

Bayu Jayawardhana
Engineering and Technology Institute Groningen

Faculty of Science and Engineering
University of Groningen

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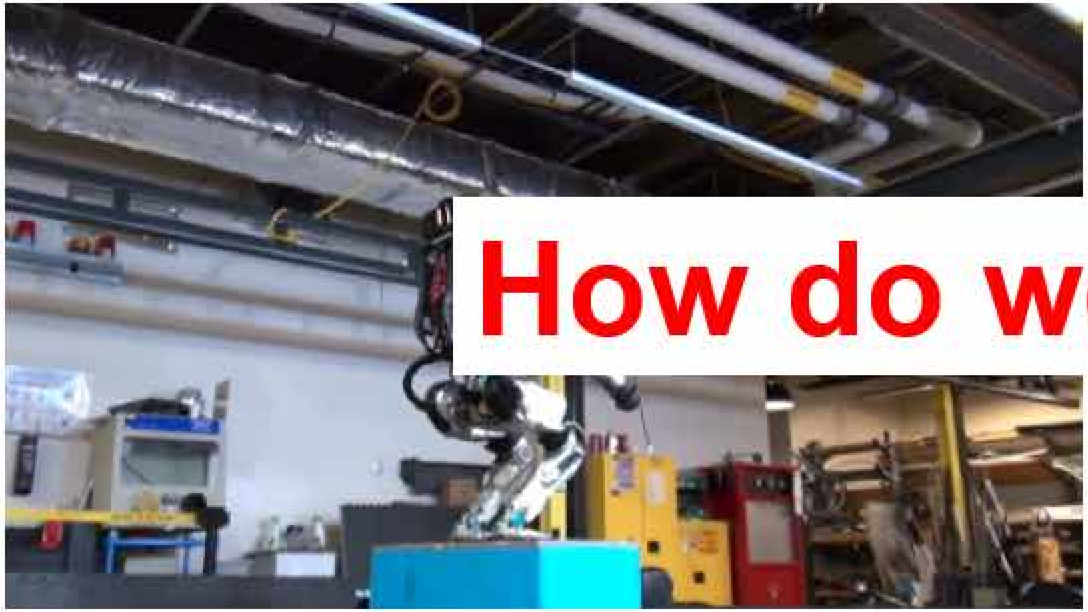
Contents

Ubiquity of control systems

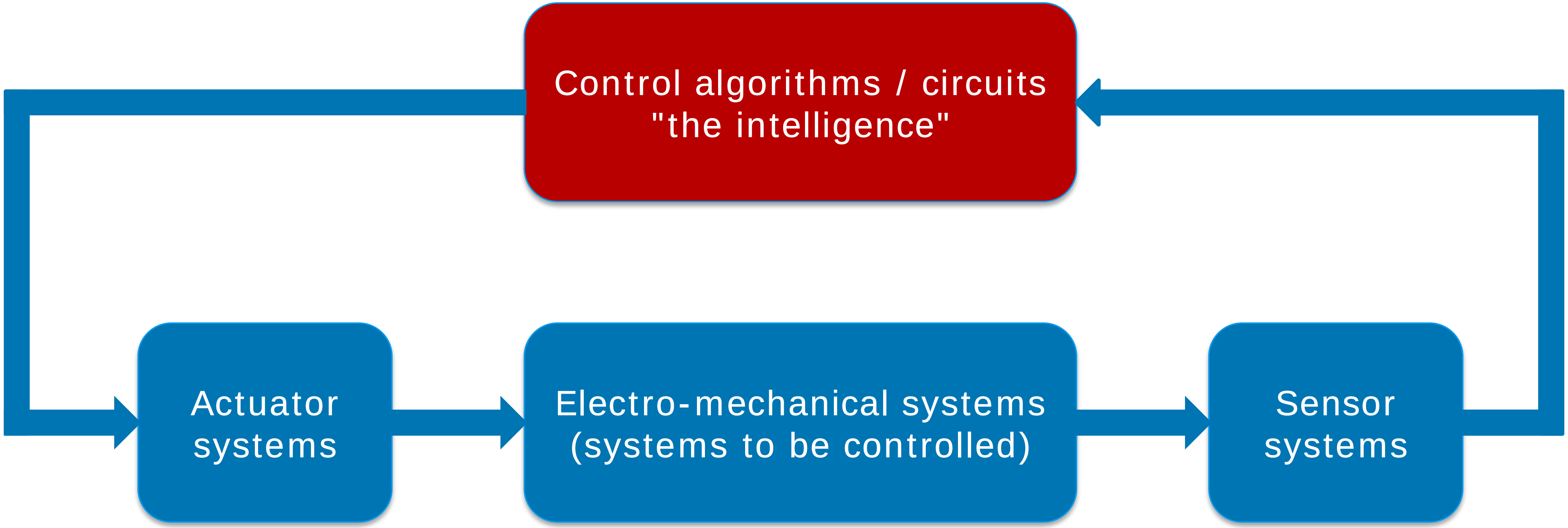
- It is a hidden technology
- Key technology for smart and autonomous systems



How do we do that?

Ubiquity of control systems

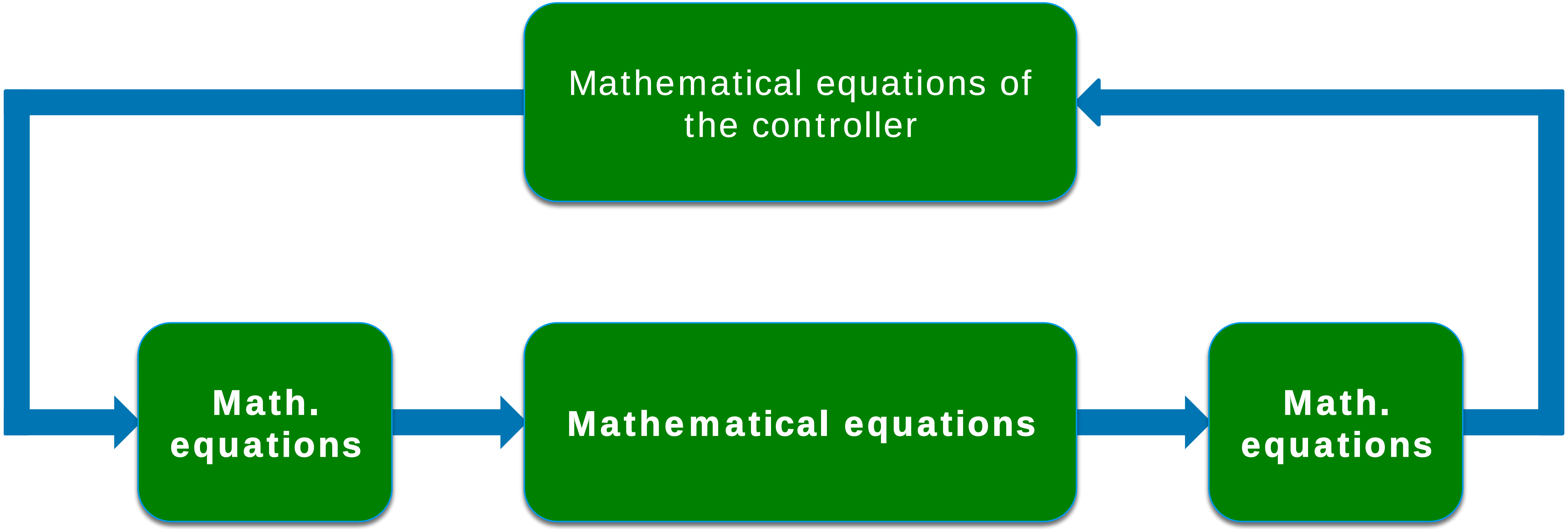
- It is a hidden technology
- Key technology for smart and autonomous systems



Ubiquity of control systems

Mathematical abstraction

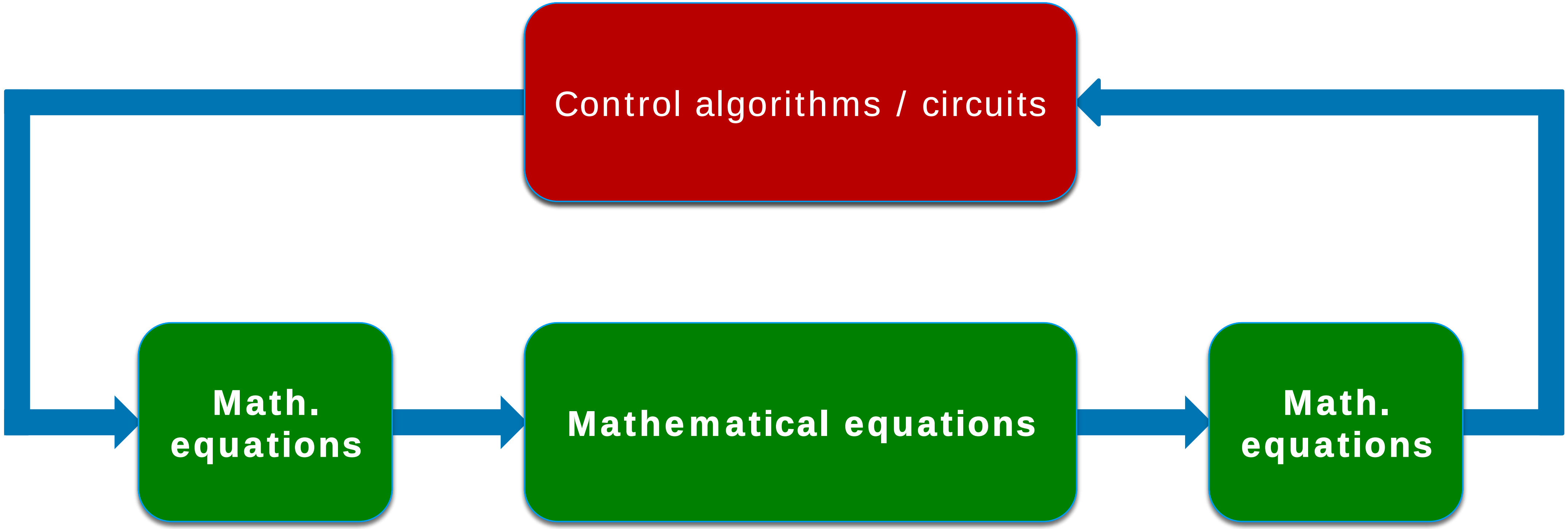
Desired dynamical behavior
of the closed-loop systems



Ubiquity of control systems

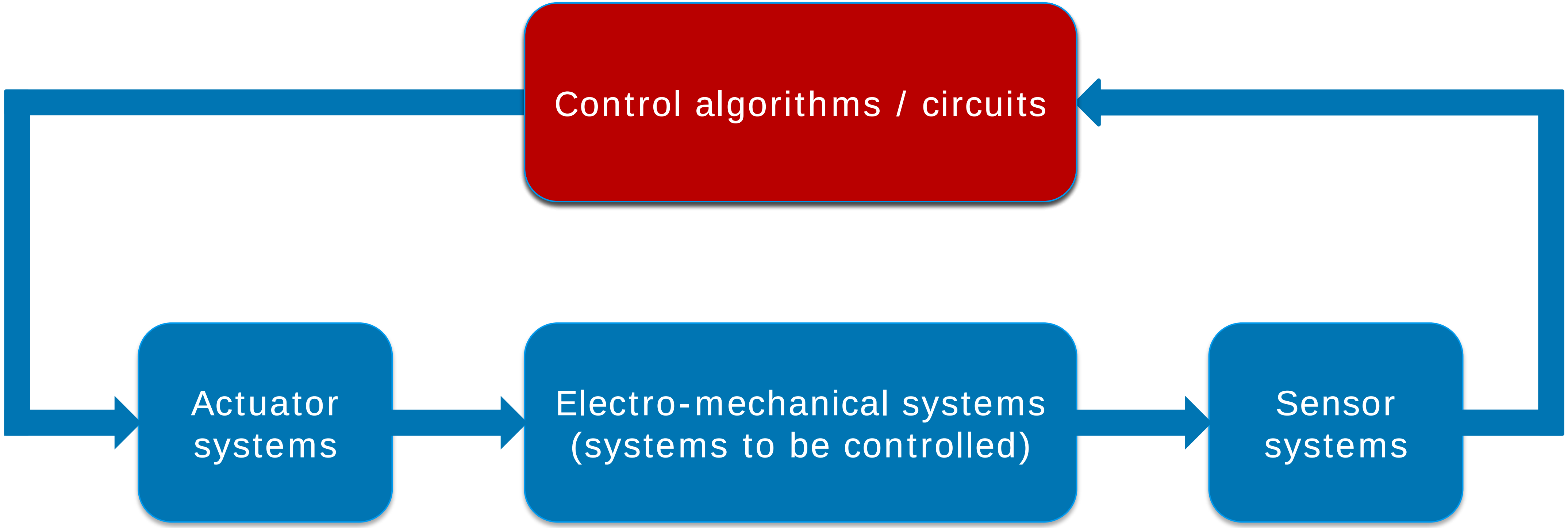
Mathematical abstraction

Translation to
computer code / to computer analog / to circuits



Ubiquity of control systems

Back to the physical systems



Collaborative (heterogeneous) autonomous systems

- A group of autonomous systems collaborate to achieve **common goal** together
- They should be **adaptive** and **robust**
- The decision making should be **distributed** as much as possible (avoiding the need of centralized computation)

Credit: "Rush Hour" by Fernando Livschitz

Collaborative autonomous systems

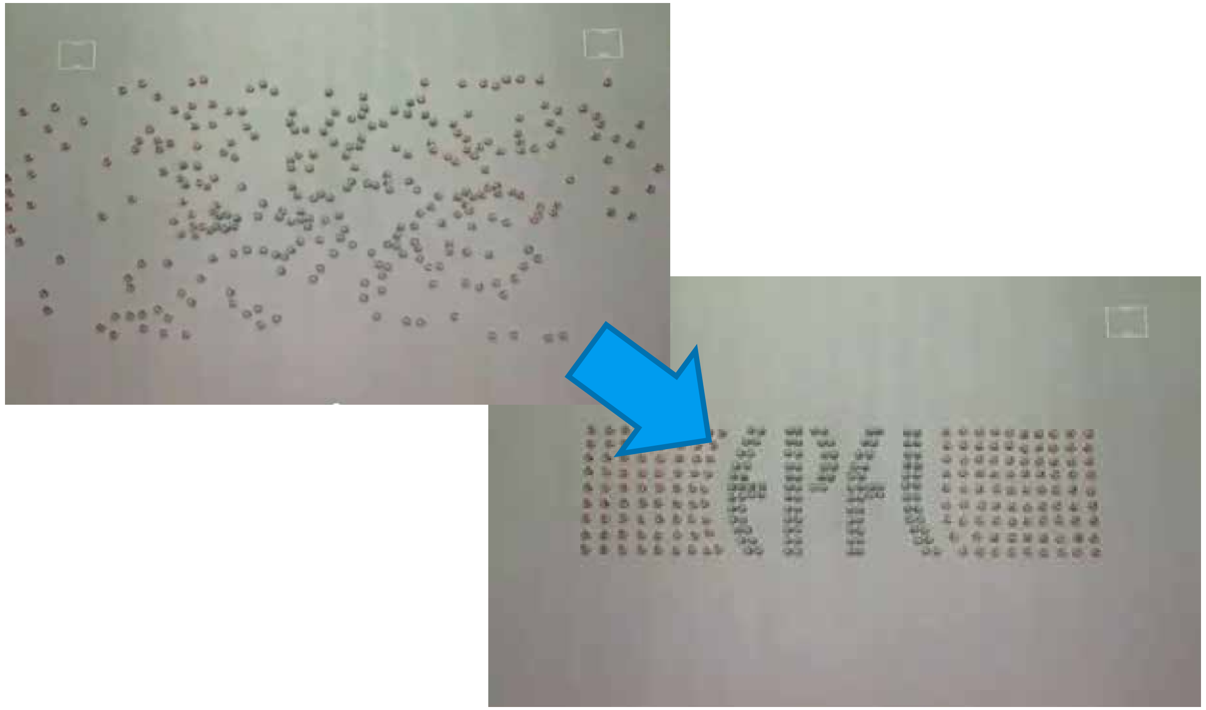
- In practice, they are mostly done **centrally** (with centralized controller & sophisticated communication and localization devices)
- Local decision making as human drivers can also induce **undesirable** collective behaviour

Winter Olympics in South Korea

Mobile robots in Smart Logistics
Ali Express (Ali Baba)

Traffic jam induced by irregularities
in the driving behavior

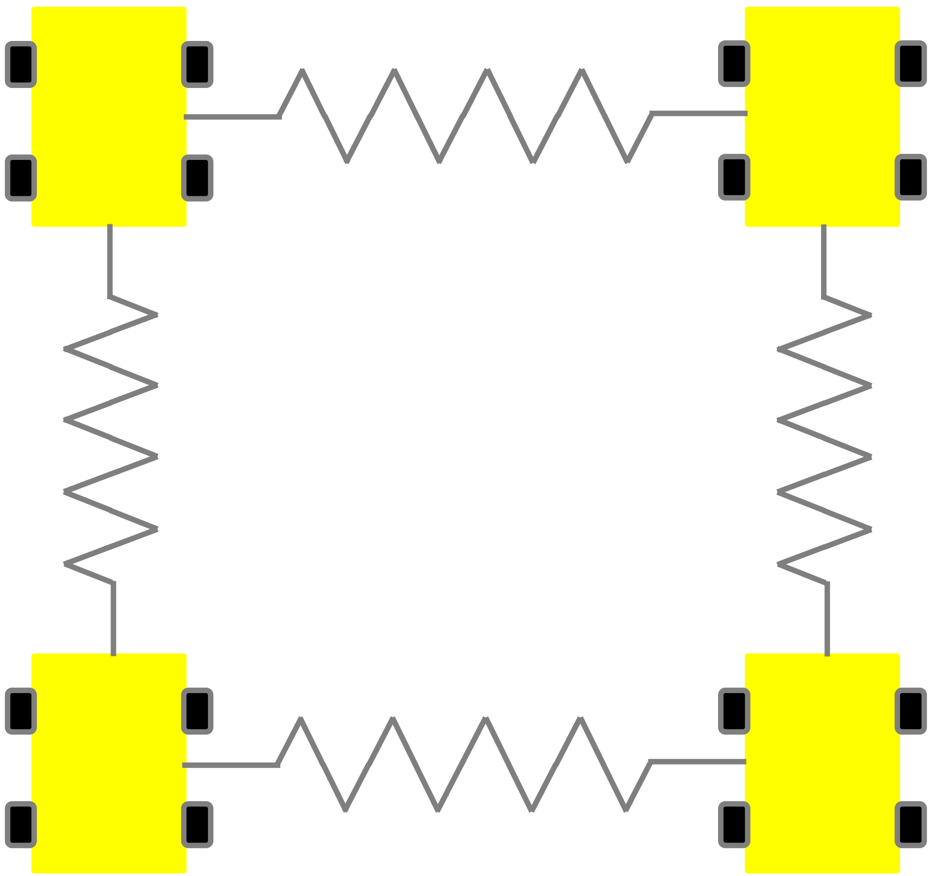
Some misleading (/fake) videos



Collaborative autonomous systems

- Some basic tasks for the team work (done in our group):
  - **Formation keeping**. Robust against uncertainties and persistent noise
  - **Group motion**. The team can move together synchronously and keep the formation intact
  - **Obstacle avoidance**. The group should be able to avoid obstacle without compromising the formation
  - **Collaborative simultaneous localization and mapping**. The group is able to map its environment and locate themselves in a distributed way
  - **Formation in task space**. When manipulator arms are used, its end-effectors should be able to maintain a given formation
  - ***Many more***

Formation control



Each link represents **local measurement** (such as, relative position, distance, bearing, etc.)

In most cases, all agents use the same information/measurement.

The use of heterogeneous sensor systems in each agent introduces some challenges.

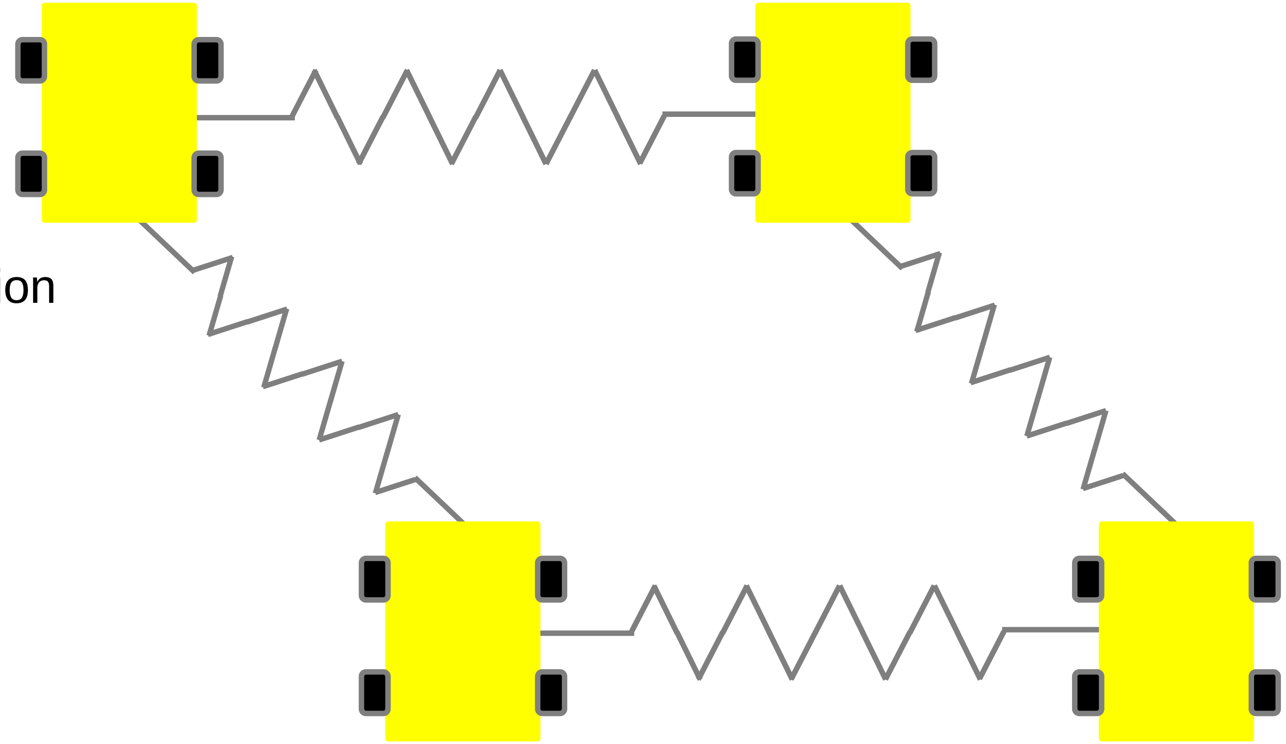
Assumption
The dynamics of each robot is assumed as **a simple integrator**.
In other words, we can directly actuate **its velocity** in 2D/3D space.

H. Garcia de Marina, M. Cao, and B. Jayawardhana, “Controlling rigid formations of mobile agents under inconsistent measurements,” IEEE Trans. Robot., vol. 31, no. 1, pp. 31–39, Feb. 2015.

Formation control

When each link defines distance constraint, then the geometric shape is not well-defined

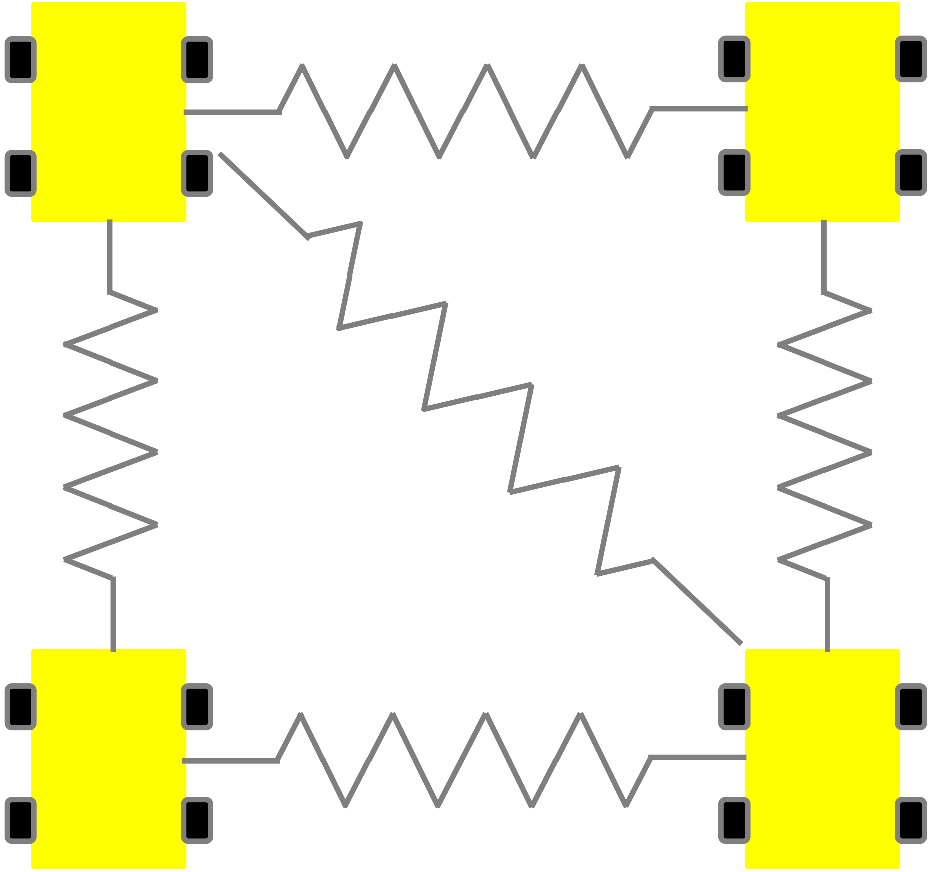
Non-rigid formation



Formation control

Distributed formation control law (distance-based gradient control):

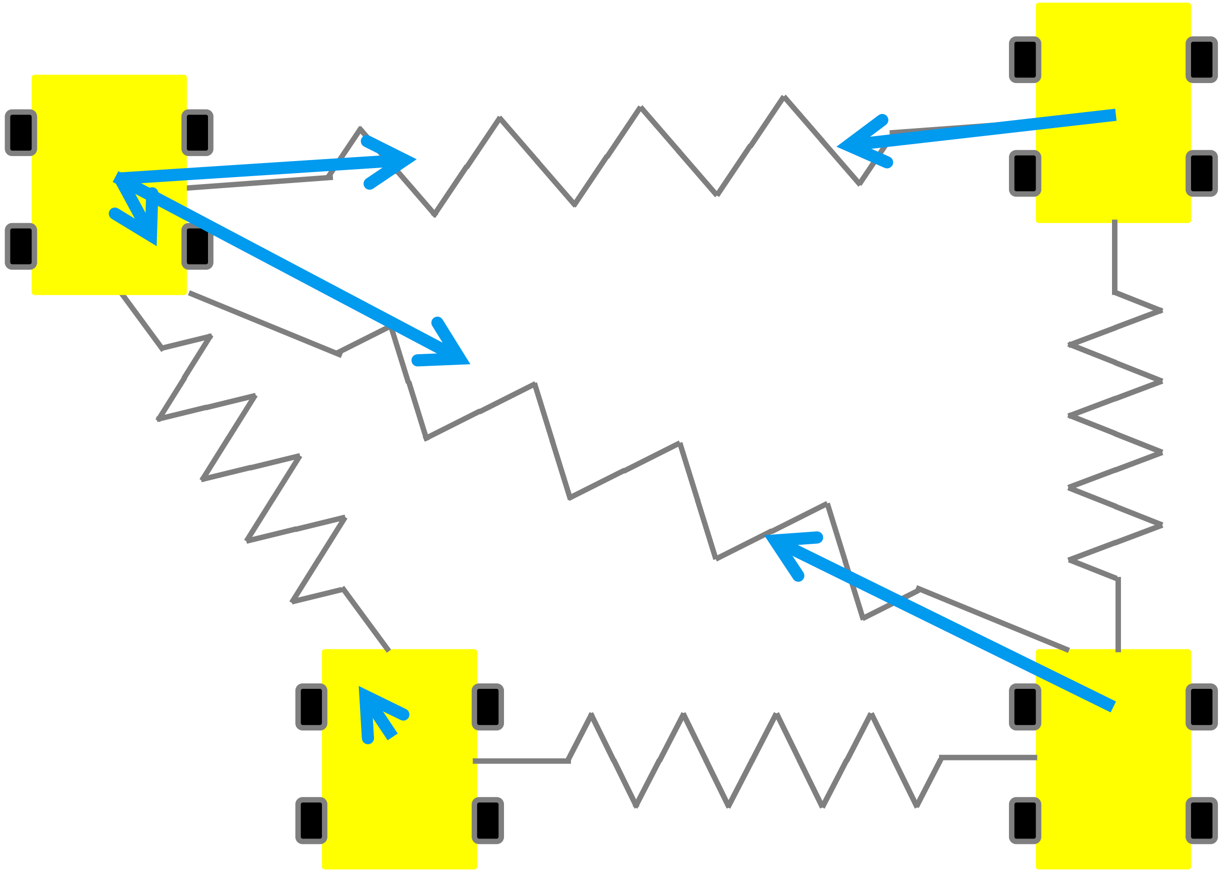
Velocity of each vehicle
= Sum of (**direction to the i-th neighbour** x **distance error to i-th neighbour**) over all neighboring agents



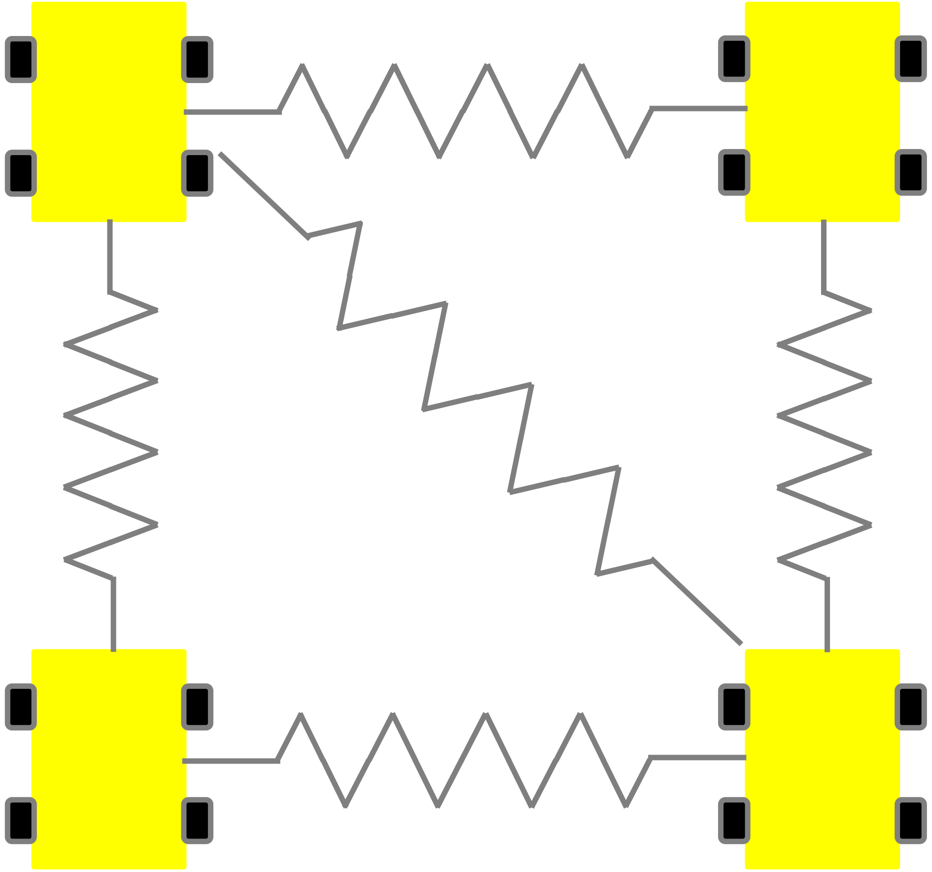
With extra link/measurement, a rigid formation can be created
(the so-called infinitesimally rigid formation)

H. Garcia de Marina, M. Cao, and B. Jayawardhana, “Controlling rigid formations of mobile agents under inconsistent measurements,” IEEE Trans. Robot., vol. 31, no. 1, pp. 31–39, Feb. 2015.

Formation control



Formation control with disturbance compensation



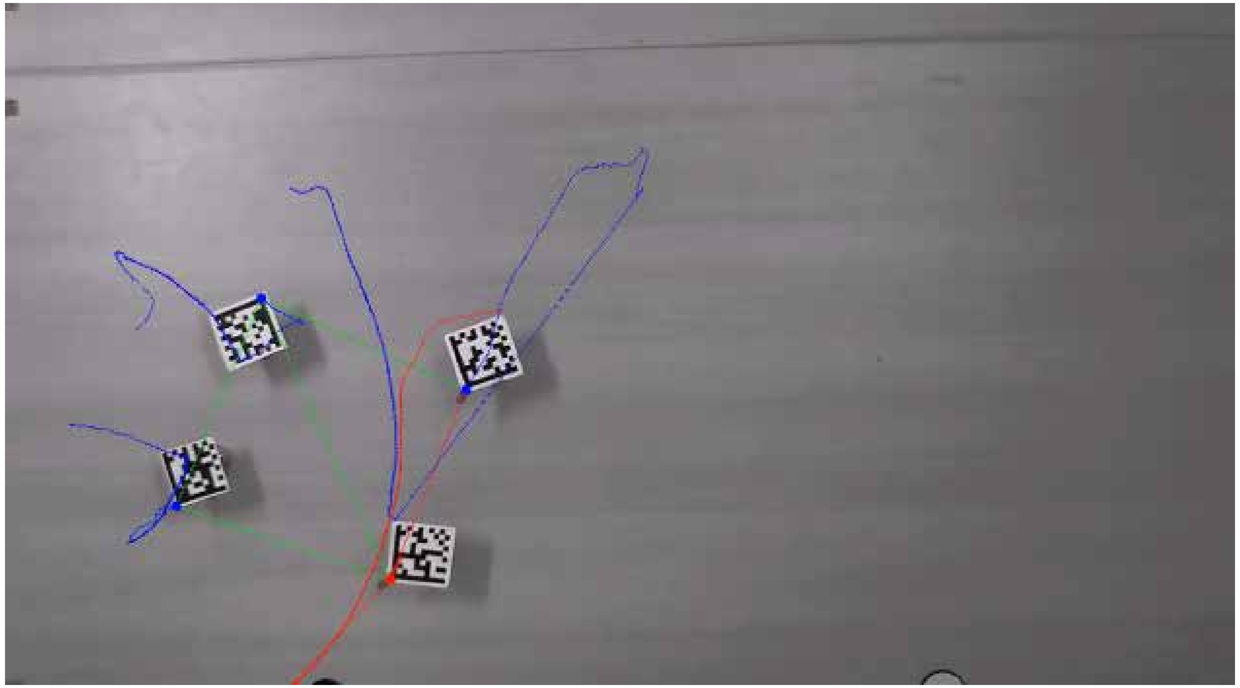
Distributed formation control law with noise compensation (distance-based gradient control + noise estimator):

Velocity of each vehicle
= Sum of (**direction to the i-th neighbour** x **distance error to i-th neighbour**) over all neighboring agents + **correction term from local estimator**

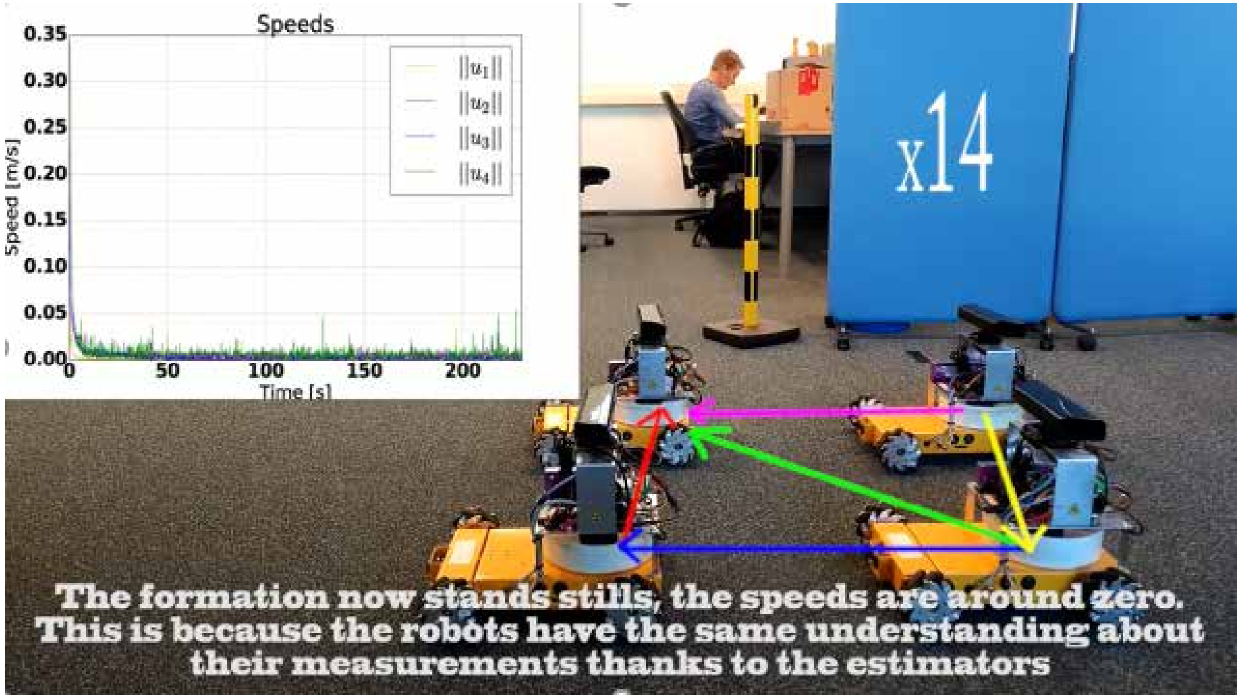
Local estimator state = **previous estimator state** + **term that depends on the error to the neighbor**

H. Garcia de Marina, M. Cao, and B. Jayawardhana, "Controlling rigid formations of mobile agents under inconsistent measurements," IEEE Trans. Robot., vol. 31, no. 1, pp. 31–39, Feb. 2015.

Experiment with and without noise compensation



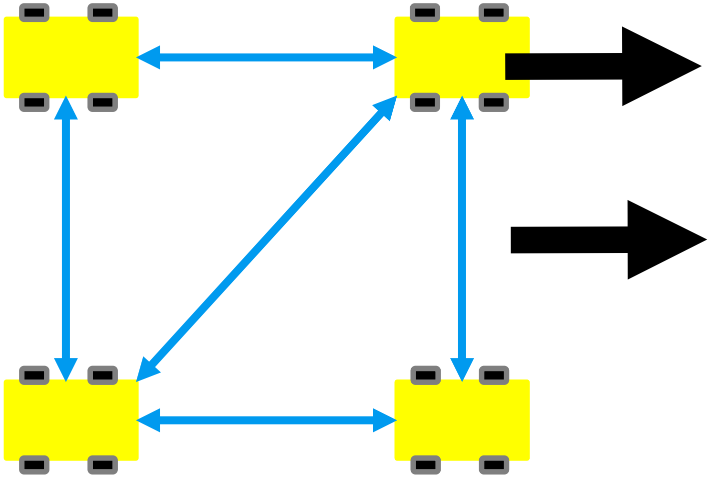
Without noise estimator and with disagreement in the desired distance between two of the agents



Robust formation where state estimator is implemented

Formation-motion control

Standard leader-follower type of group motion control law (Translation)



Formation-motion control

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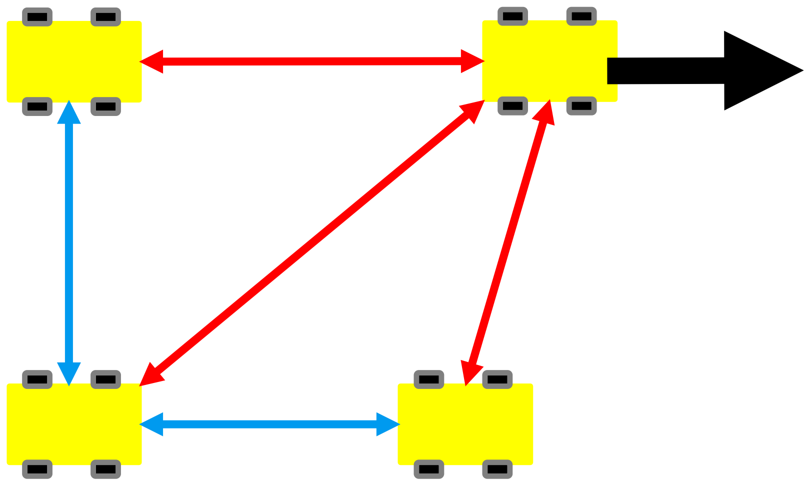

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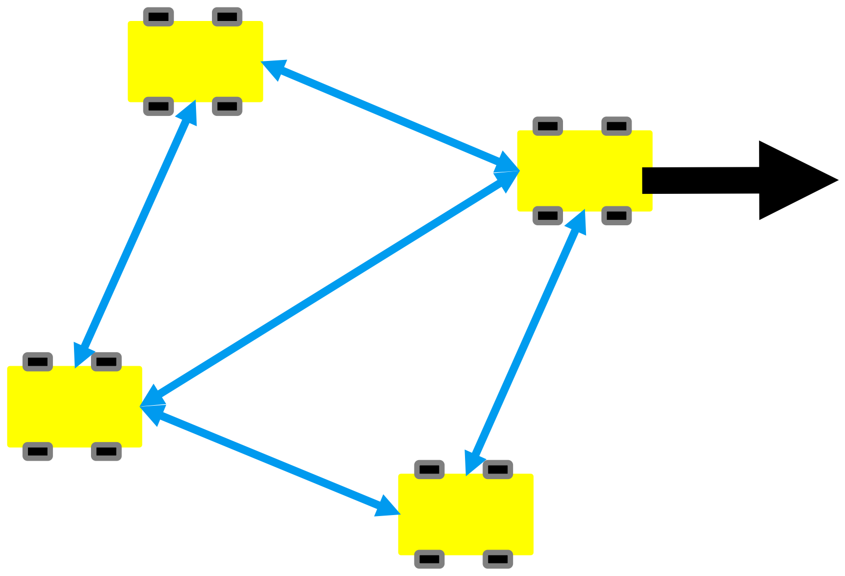

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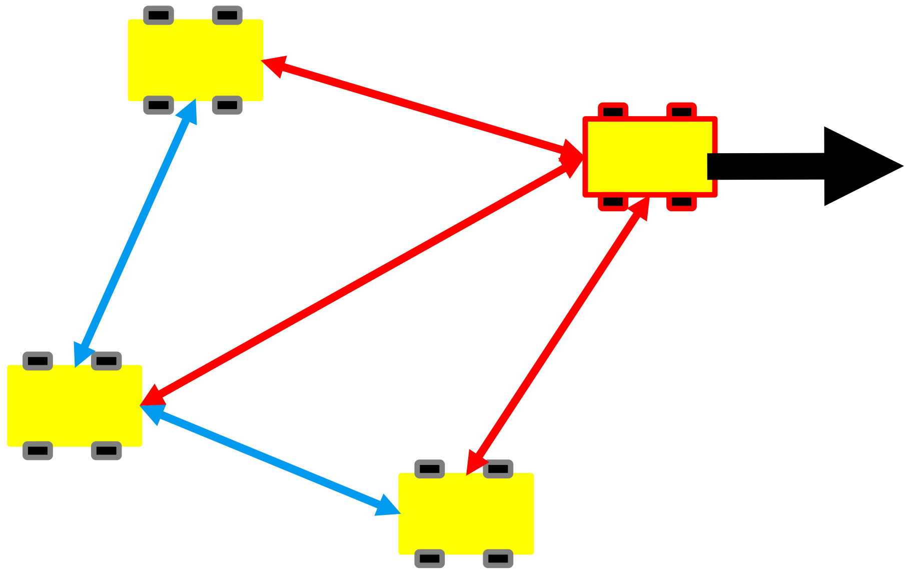

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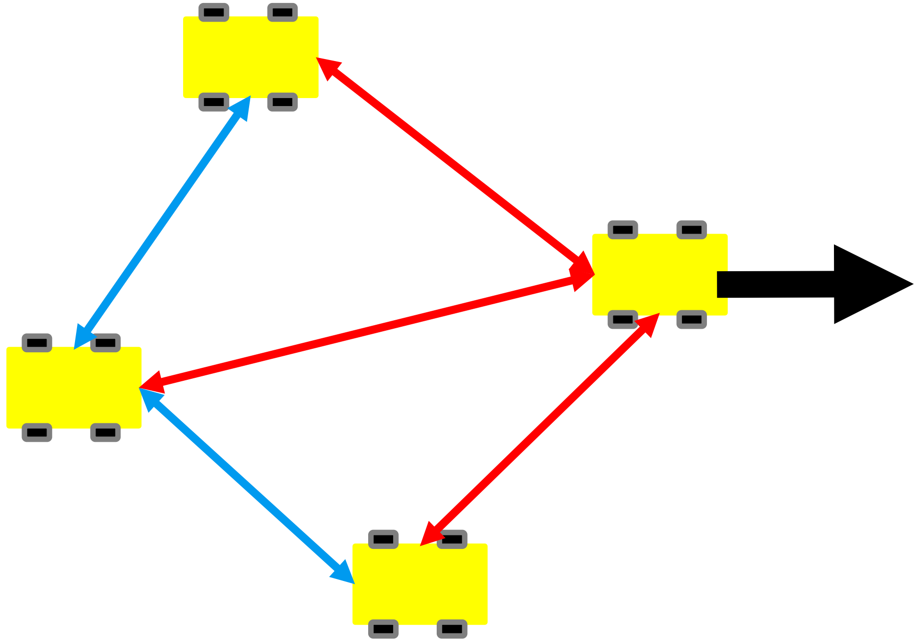

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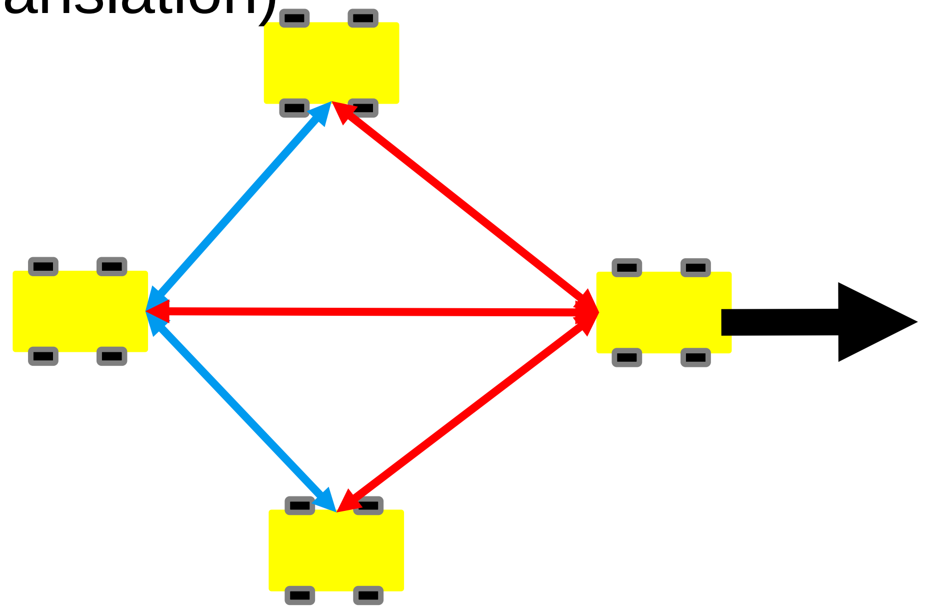

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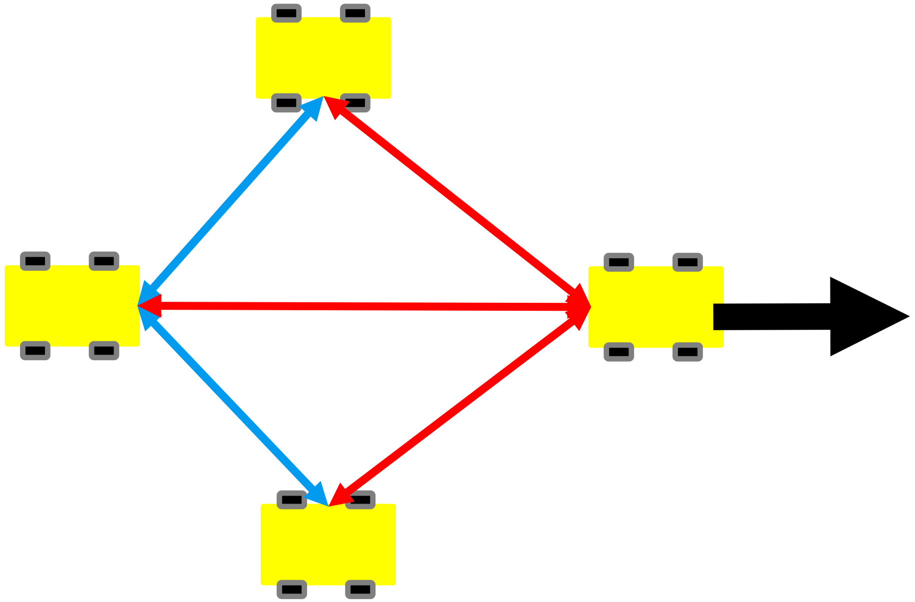

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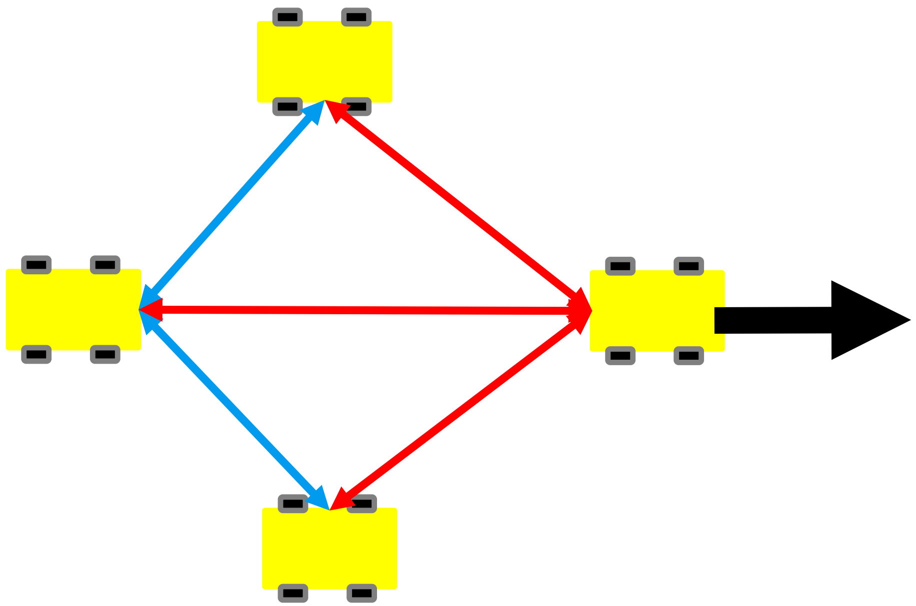

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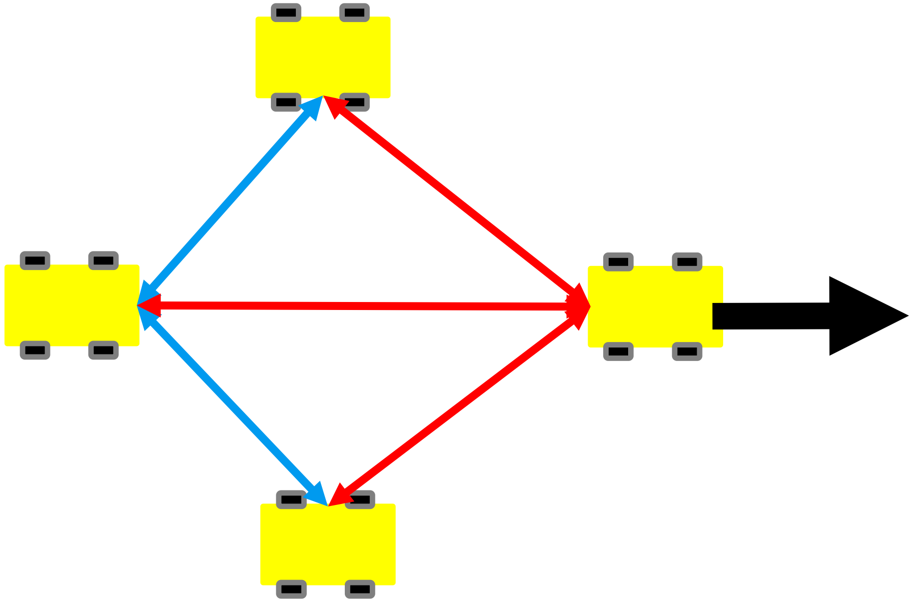
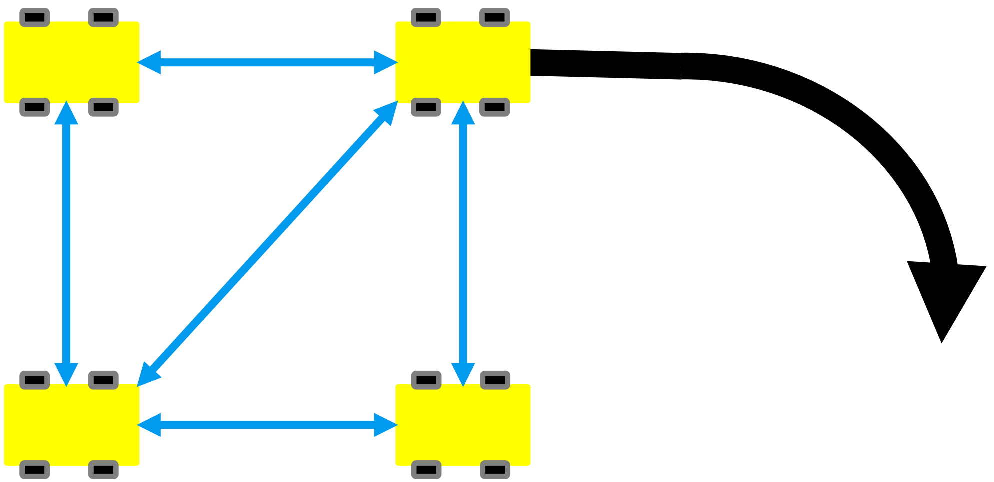


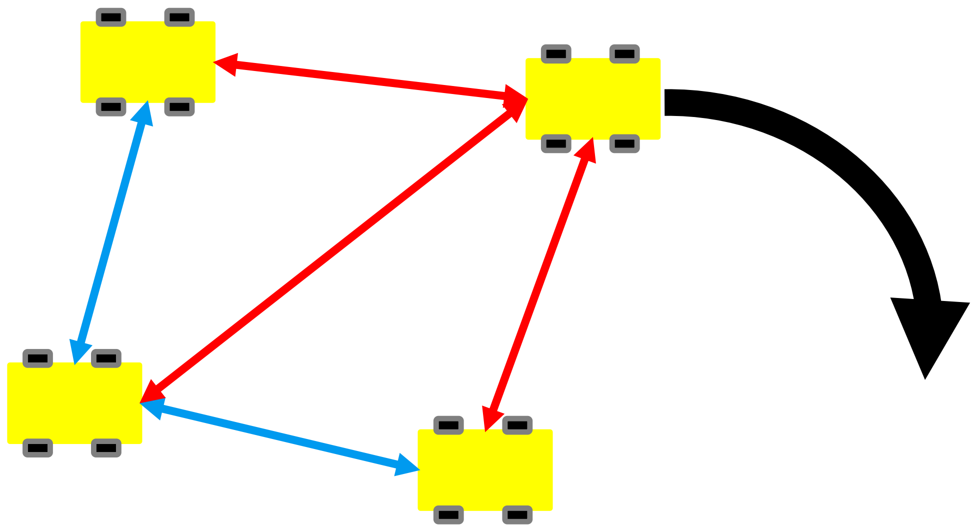
Formation-motion control

Standard leader-follower type of group motion control law (Rotational)



Formation-motion control

Standard leader-follower type of group motion control law (Rotational)



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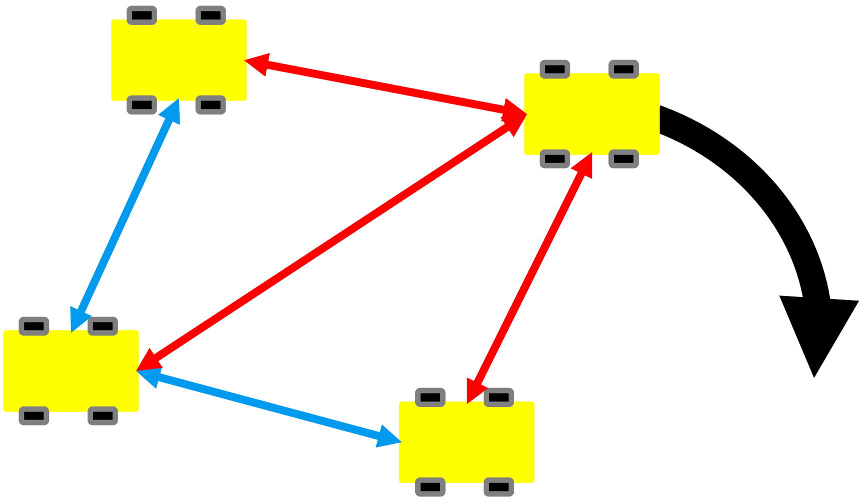

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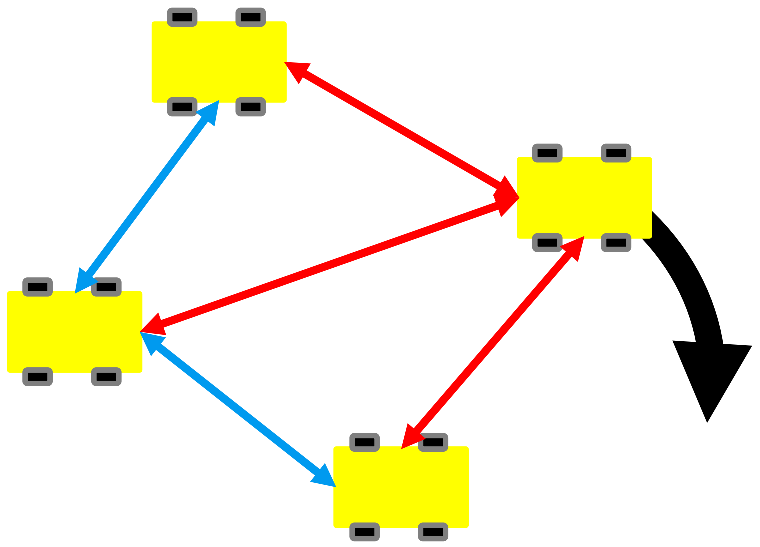

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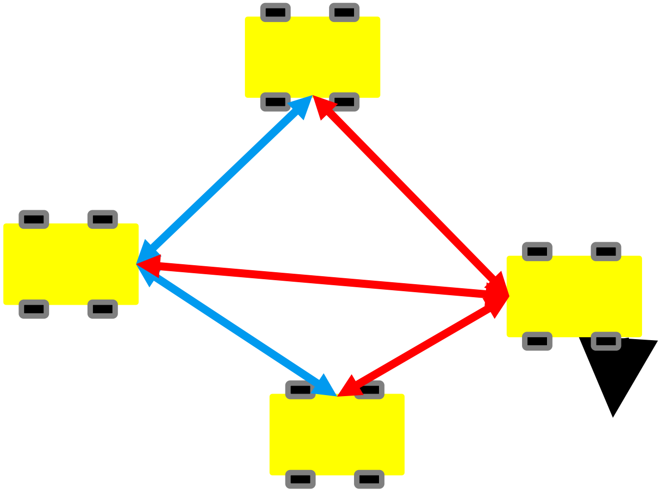
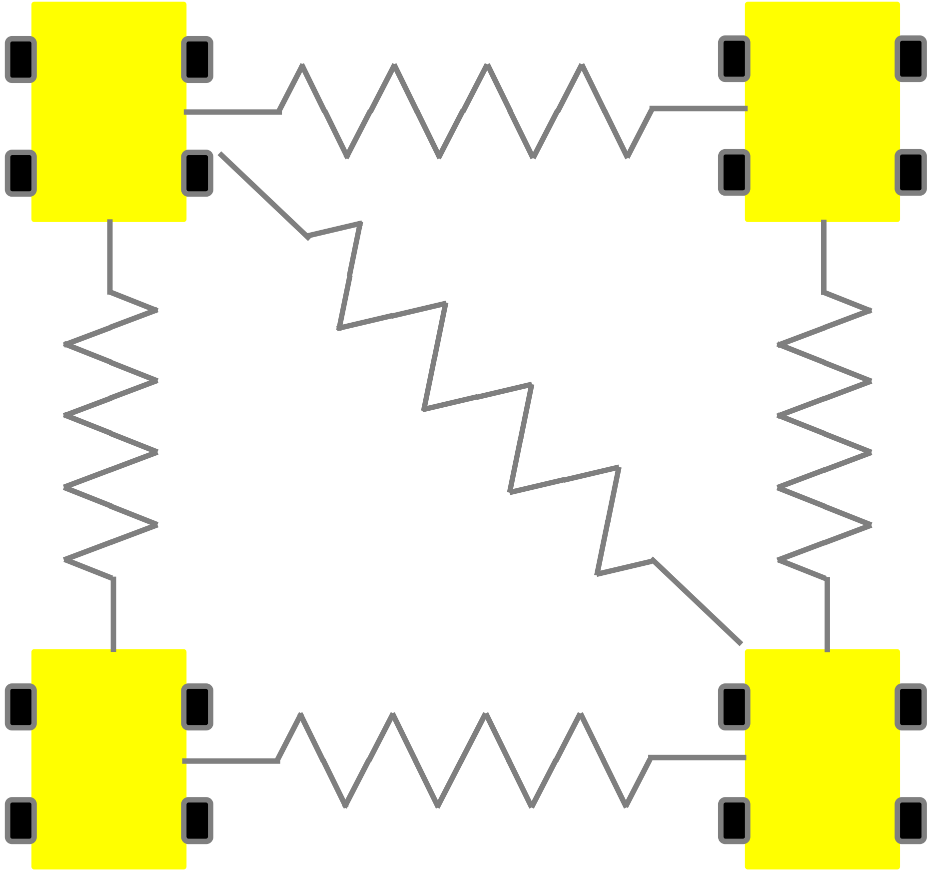


Formation-motion control



Distributed formation-motion control law (distance-based gradient control):

Velocity of each vehicle
= Sum of (**direction to the i-th neighbour** x **distance error to i-th neighbour**) over all neighboring agents

Distance error = function(**desired distance**, **desired group motion**)

The computation & assignment of the motion parameters is done **centrally** by an orchestrator, and they are constant and sent **once**, until a new motion is required.

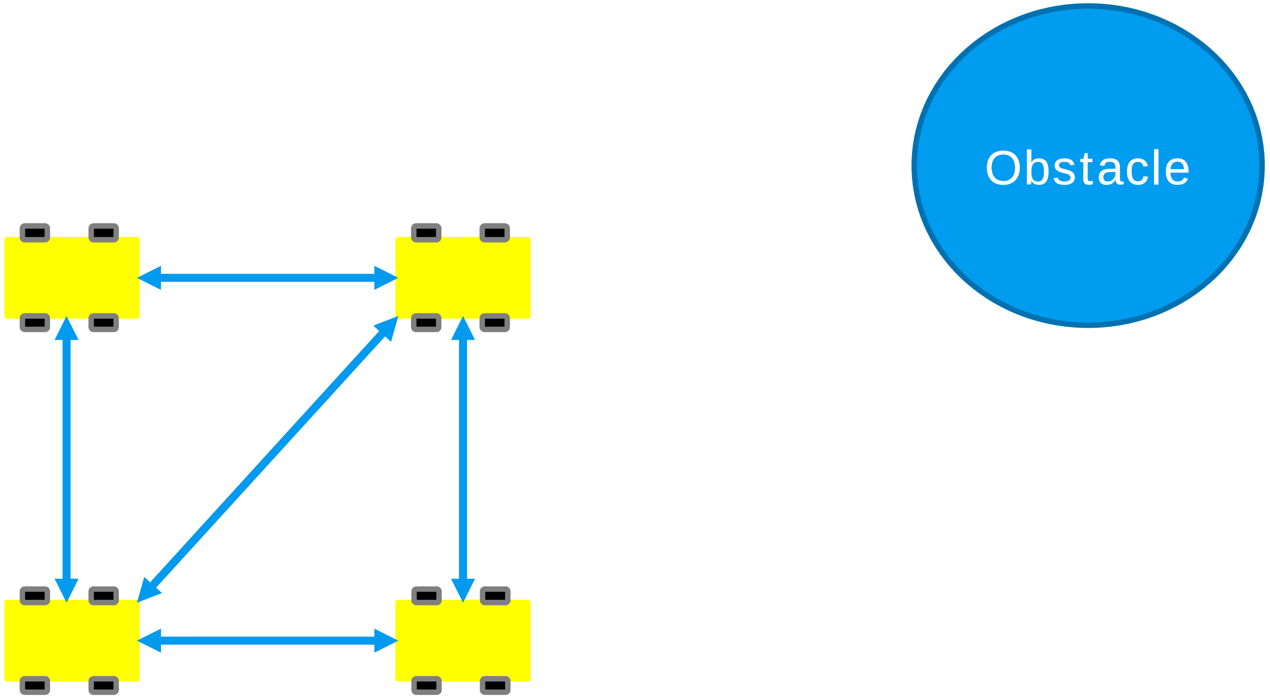
H. de Marina, B. Jayawardhana, M. Cao, "Taming Mismatches in Inter-agent Distances for the Formation-Motion Control of Second-Order Agents," IEEE Transactions on Automatic Control, 63(2), 449-462, 2018.

Formation-motion control (experiment)

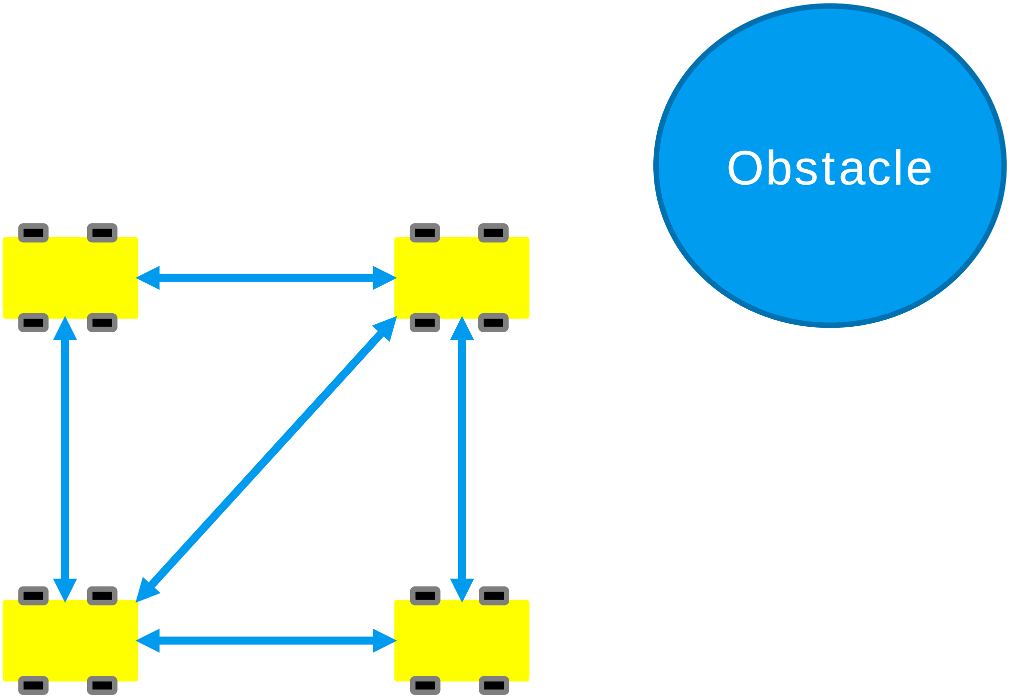
Credit: Johan Siemonsma, RUG

Credit:
Hector Marina (Universidad Complutense de Madrid) and TU Delft

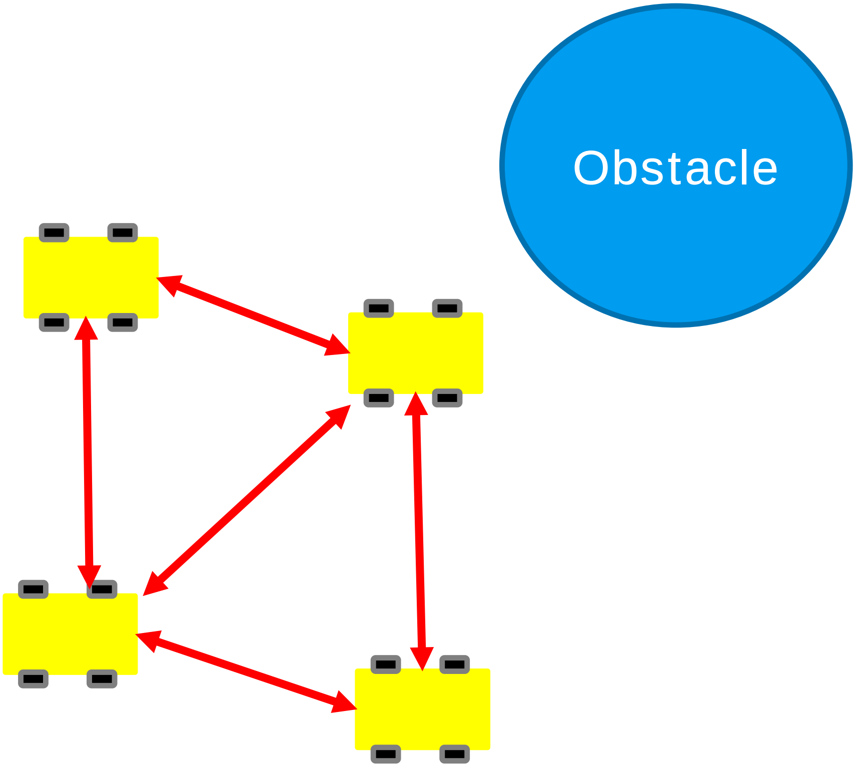
Formation-motion-obstacle avoidance control



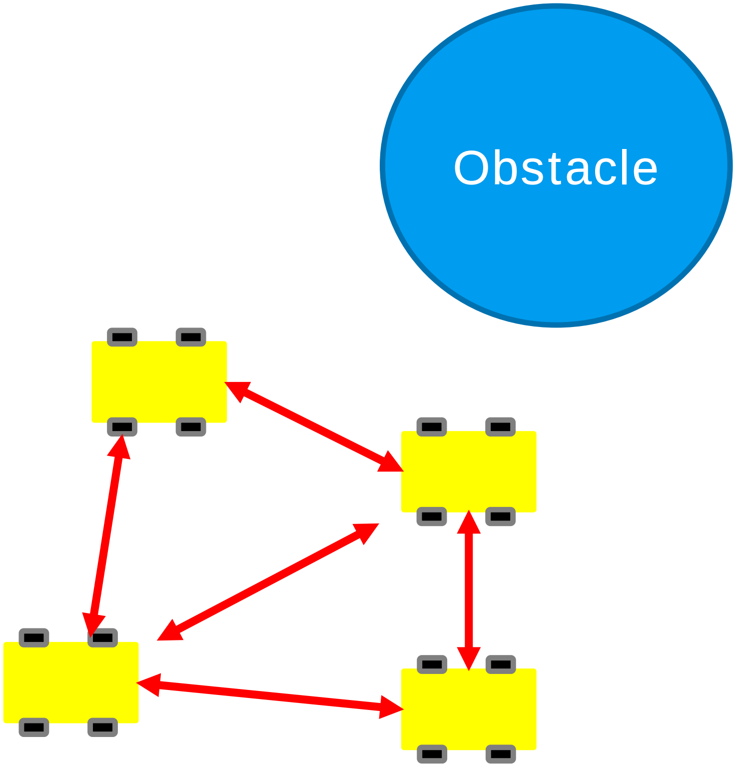
Formation-motion-obstacle avoidance control



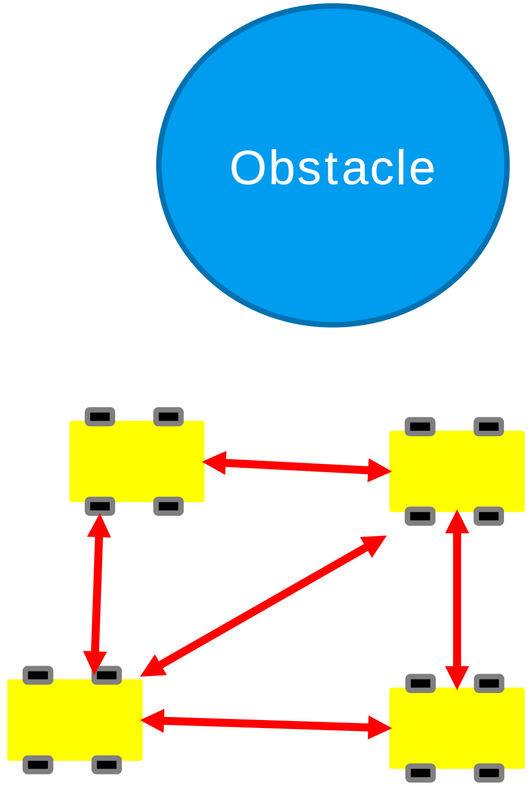
Formation-motion-obstacle avoidance control



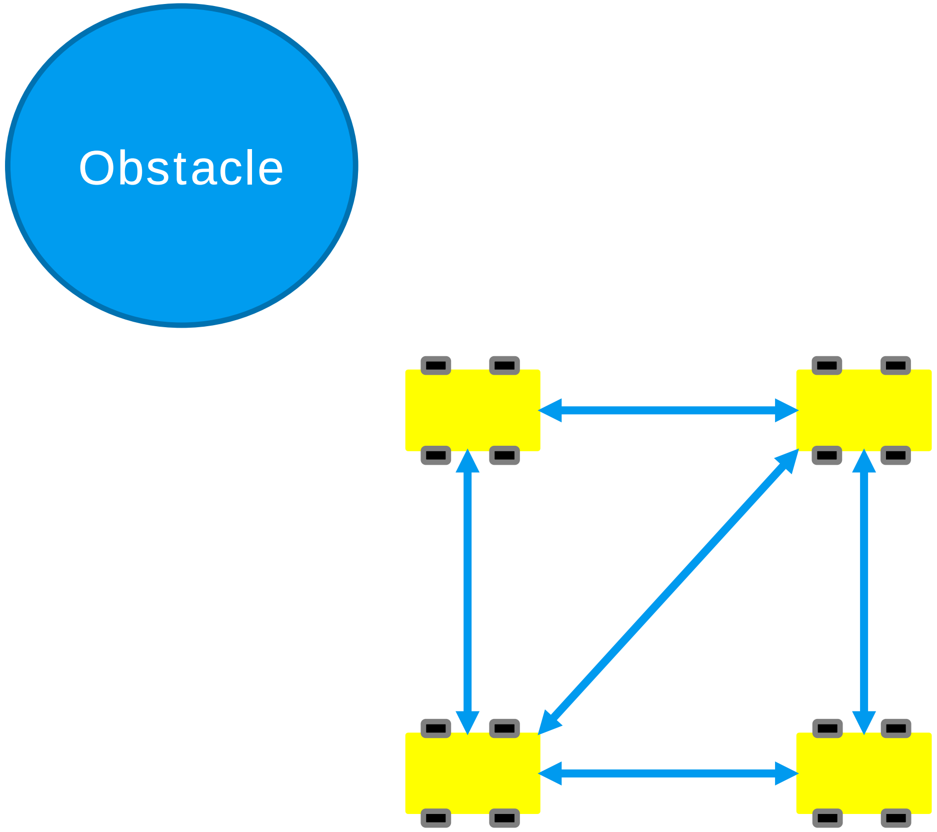
Formation-motion-obstacle avoidance control



Formation-motion-obstacle avoidance control



Formation-motion-obstacle avoidance control



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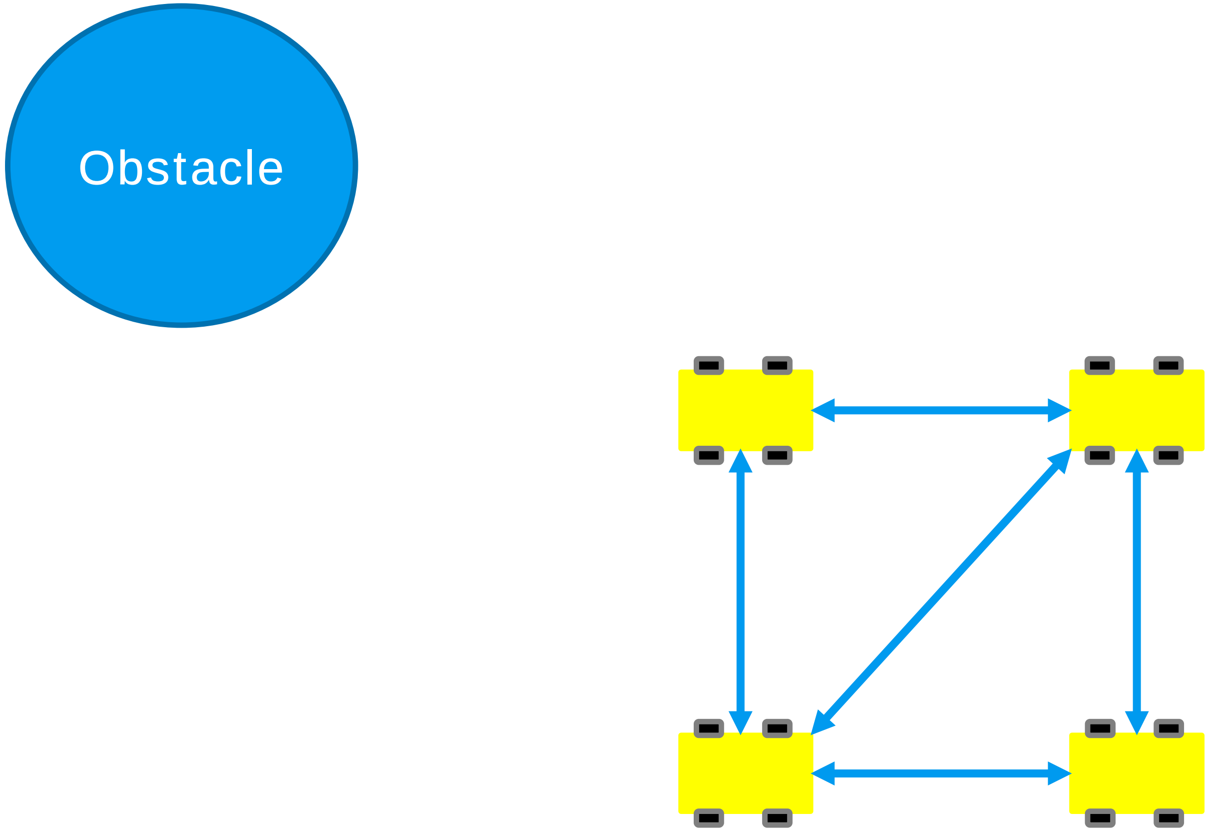

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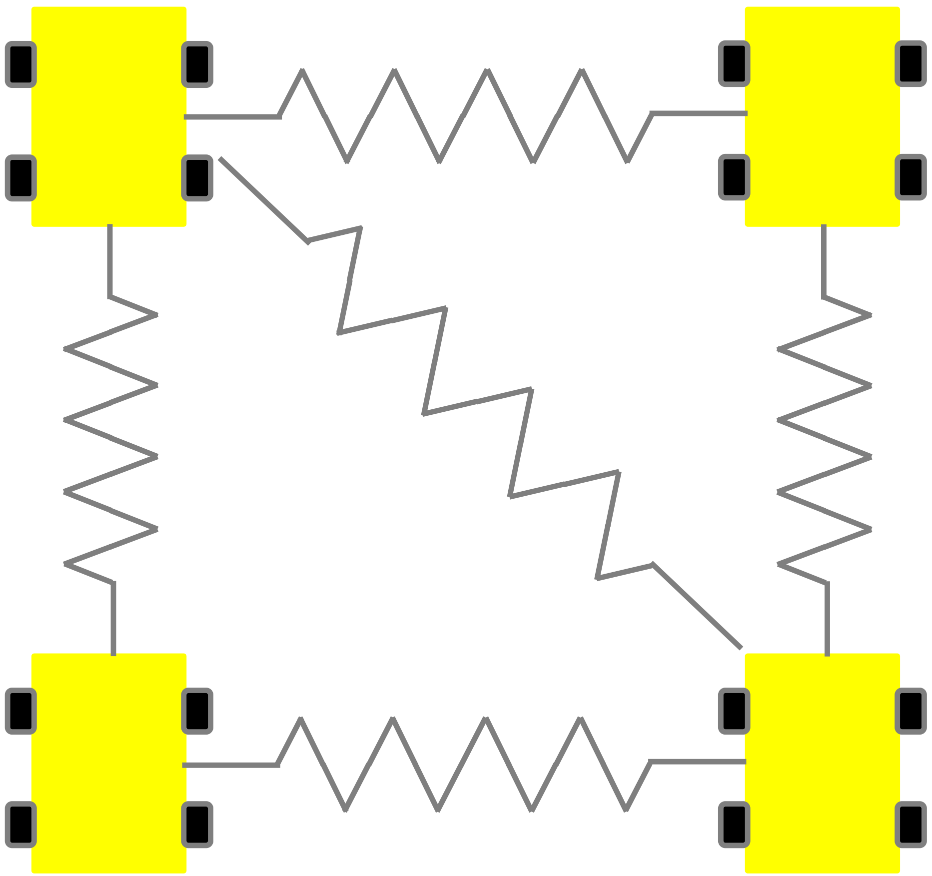
Formation-motion-obstacle avoidance control



Distributed formation-motion-obstacle avoidance control law (distance-based gradient control):

Velocity of each vehicle
= Sum of (**direction to the i-th neighbour** x **distance error to i-th neighbour**) over all neighboring agents + **local obstacle avoidance estimator**

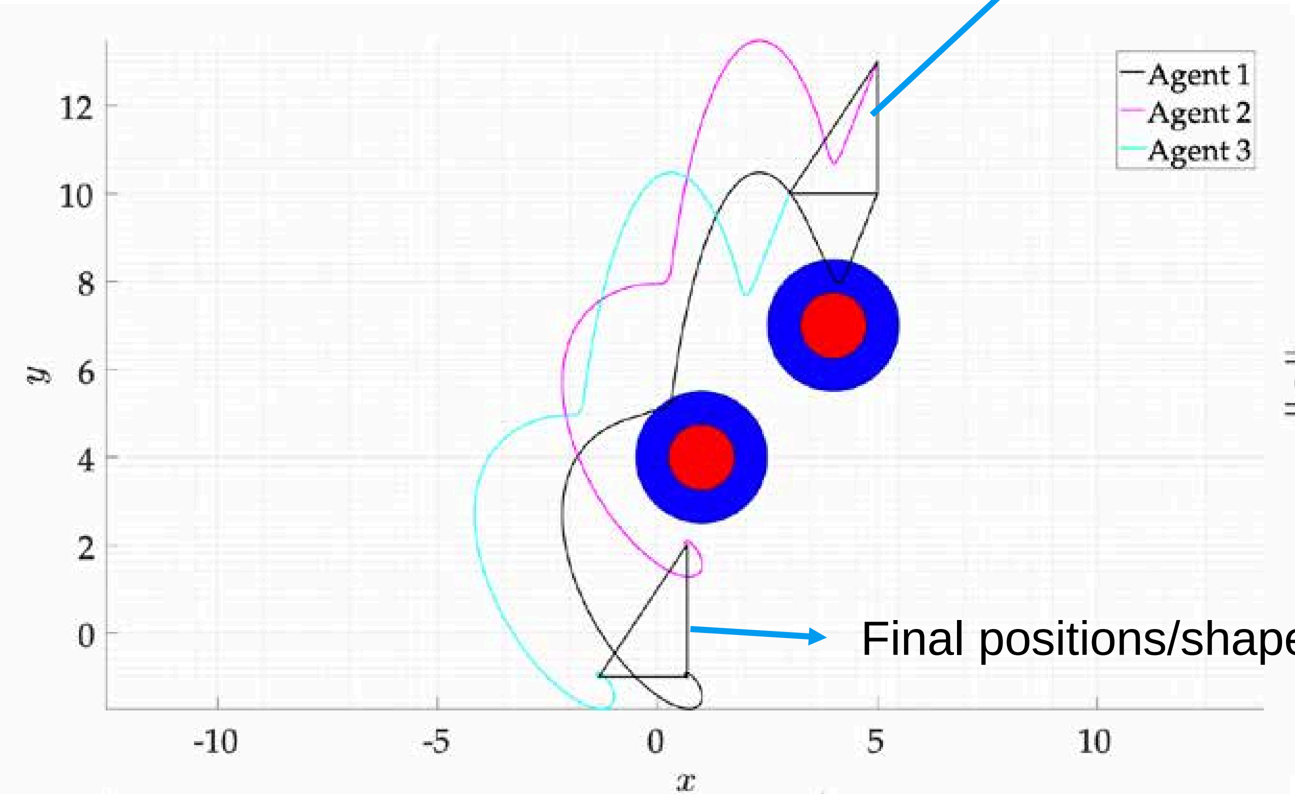
Local obstacle avoidance estimator = **current estimator state**
+ **local repulsion control law**
+ Sum of (**neighboring obstacle avoidance estimator state**)

N.P.K. Chan, B. Jayawardhana, J.M.A. Scherpen, "Distributed Formation with Diffusive Obstacle Avoidance Control in Coordinated Mobile Robots," 57th IEEE Conf. Decision & Control, pp. 4571-4576, 2019.

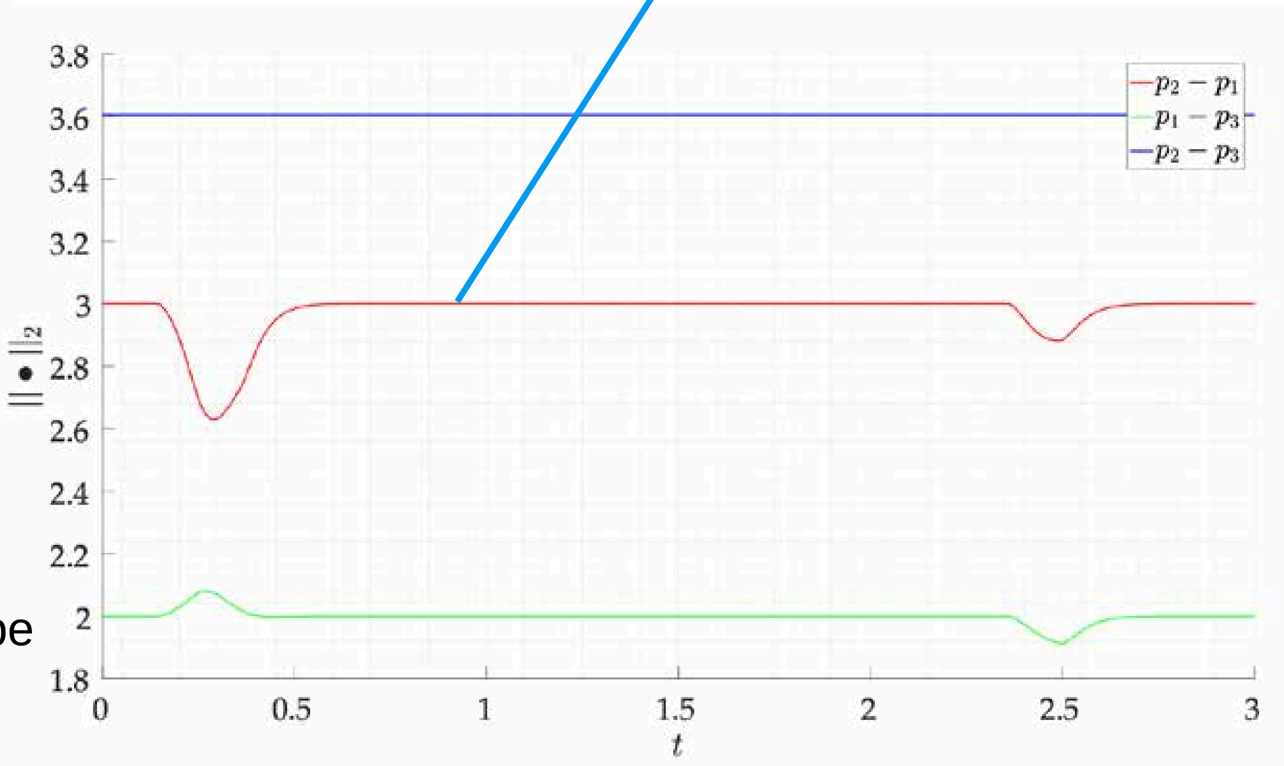
Formation-motion-obstacle avoidance control

Initial positions/shape

Throughout the transition, the deformation of the shape is minimal



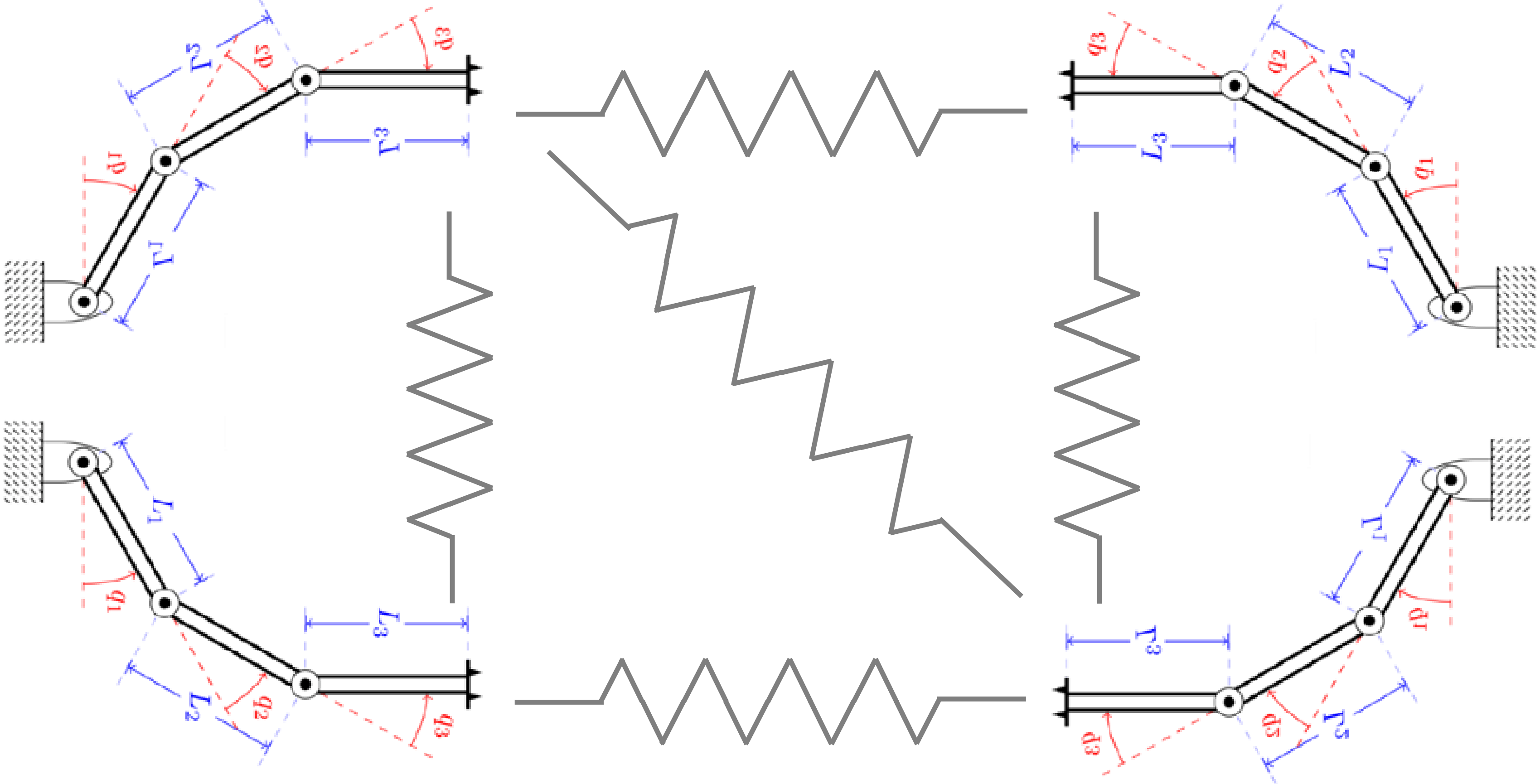
Final positions/shape



Plot of motions of 3 agents in the xy-plane that maintain their formation while converging to the origint

The plot of transient behaviour of the inter-distance between the three agents while moving towards the origin

Formation control in task space (on-going work)

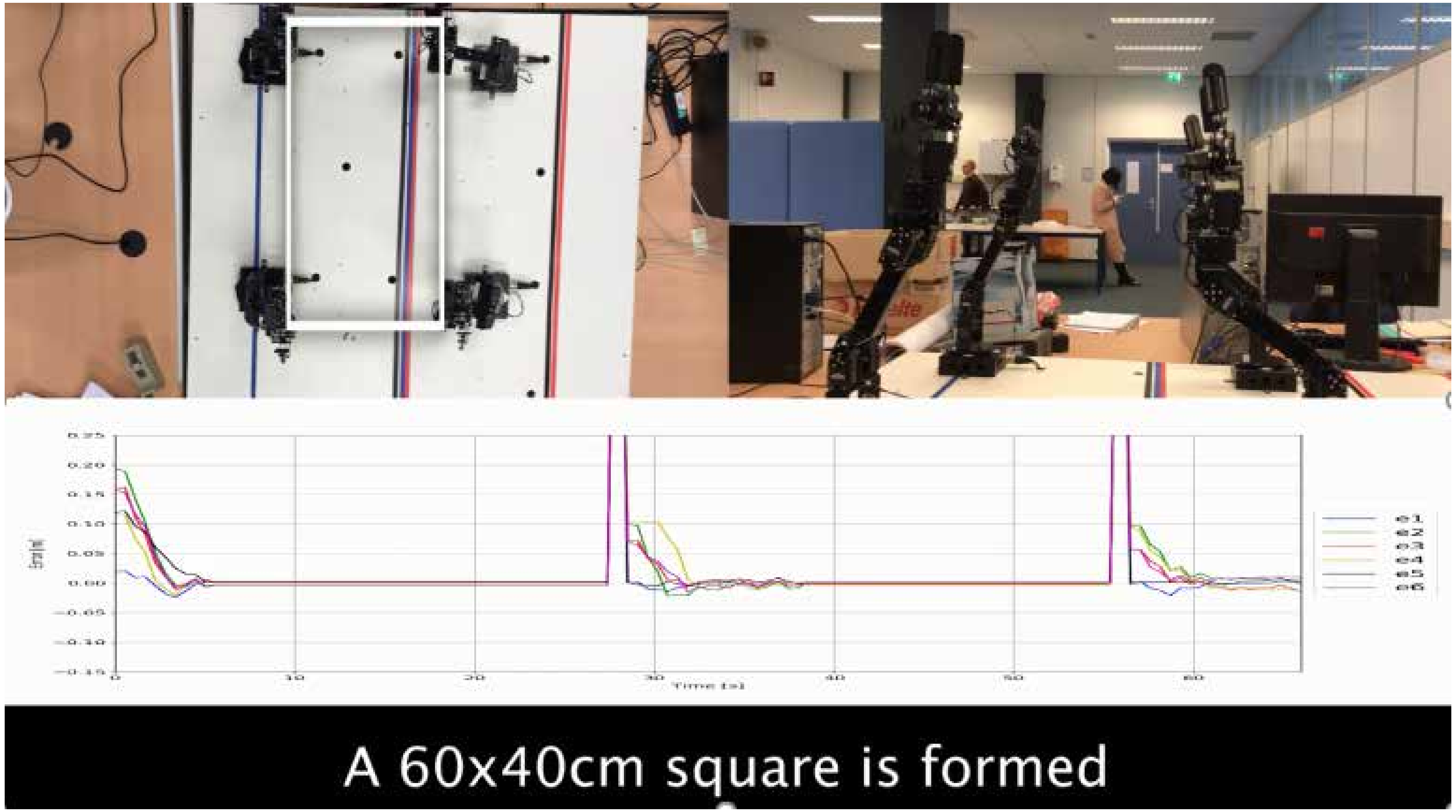


Distributed formation in task space control law (distance-based gradient control):

Desired velocity of end effector = Sum of (**direction to the i-th neighbour** x **distance error to i-th neighbour**) over all neighboring agents

Joint forces = functional operator of the joint displacements, joint velocities, and desired velocity of end effector

Formation control in task space (on-going work)



Perspectives

- The development of distributed control for collaborative autonomous systems **enable** guaranteed performance of the team based only on **local measurement** and **local coordinate frame**
- The real-time communication network among agents can subsequently be used for **higher-level tasks**. For instance:
  - Collaborative simultaneous localization and mapping
  - 3D real-time sensor networks (for environmental monitoring, etc.)
  - Realizing solutions for smart logistics and smart factory

Thank you

› Mechatronics and Robotics team within the Discrete Technology and Production Automation group:
  - Prof. Jacquelien Scherpen, Prof. Ming Cao and colleagues of Jan-Willem Center for Systems and Control
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  - ir. Sietse Achterop, ir. Martin Stokroos, Simon Busman (lab coordinators)
  - Graduate students: ir. Johan Siemonsma, ir. Jeroen Biesterbos, MSc., ir. Le Pan, ir. Marijn Gelders, ir. Tim de Bakker, ir. Wiljan Vos, ir. Guido Vedder, ir. Thomas Ike, ir. Renate Bijker, ir. Vincent Samallo, ir. Mark van Biel, ir. Heleen van Wijck, ir. Laurah Kuik, ir. Johan Ziel, many more

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