Cyber-Physical Systems: Cooperative control (communication / location / decision-making) of a fleet of mobile robots

Keywords: Cyber Physical System (CPS), multi-robot system (MRS), control architecture, obstacle avoidance, short and long-term planning, control, consensus-based-control, graph theory, collaborative localization, integrity, fault detection and exclusion, state estimation, CPS topologies, quality of service for CPS communication.

Introduction

The task of coordinating a fleet of mobile robots in a congested and/or constrained environment becomes a strategic and economic issue of primary importance, particularly for applications related to: autonomous transport (see Figure 1 (a)), agriculture (see Figure 1 (b)), industry 4.0, defense, or for example related to 2D animations (cf. Figure 2) or other for large public in 3D[1]. It is for this reason that we aim in this project to address this task of generating static and dynamic formations of several mobile robots. These must be coordinated via an appropriate control architecture (coexistence of several complementary and interdependent modules: robust control / precise localization and communication with a good quality of service).

(a) (b)

Figure 1. Autonomous vehicles navigation in formation for passenger transport (a) or agricultural (b) applications

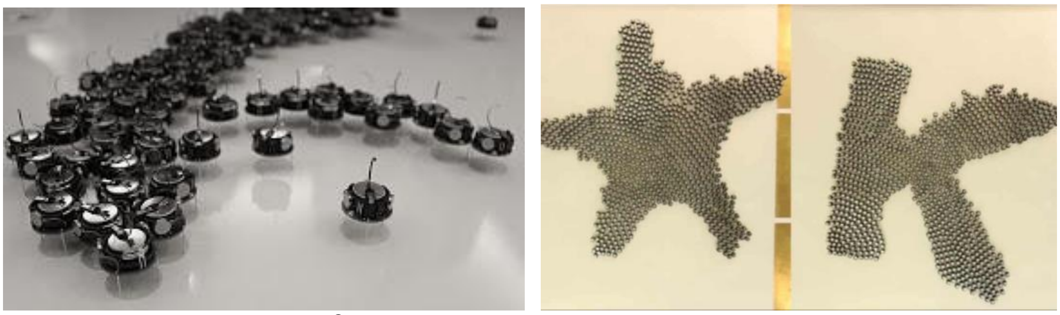

Figure 2. Swarm of Kilobots® robots with local distributed interactions to create any 2D shapes

As preliminary information, it will be provided in the final project (part II of this document) a mini-software under Matlab/Simulink containing elementary functionalities to control a Multi-Robot System (MRS) under perfect conditions location and communication, and without any hazards in the environment (e.g., without the presence of obstacles, see Figure 3). The objective will then be to adapt the working of the mini-software to explicitly carry out the

[1] Comme l'exemple donné par l'utilisation des drones en formation : https://www.youtube.com/watch?v=y0KNhSejkOI

L. ADOUANE, G. JABER, A. LIMA et M. MAHMAT

Version 30/09/2024

targeted cooperative task. It will also be a question of further developing the provided mini-software, by explicitly integrating localization and communication functionalities so that they are as close as possible to the reality of this type of MRS (highly dynamic and subject to high level of uncertainties/constraints in terms of location and communication). Thus, the final objective is to make the control of the MRS as robust as possible in the face of the hazards that you will explicitly introduce in your simulations. It will of course also be a question of proposing adaptations of the planning, control and decision-making modules under uncertainties of the MRS.

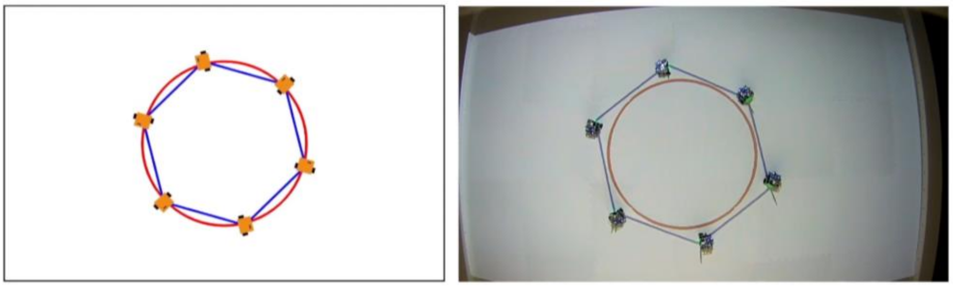

Figure 3. Cyclic tracking task, Robotarium simulation.

Part I: Bibliographic study and development of basic functionalities

The objective of this first part of the project is to have the opportunity to explore and investigate, though a bibliographic research the large world of CPS in a field not immediately linked to the navigation of multi-vehicle systems (MVS), but to other kinds of CPS, having at once, tight correlation between the three of the major themes addressed in SY28/AI34: (control/planning/decision-making), the communication and the localization parts.

Several possible examples of CPS are already shown in the first slides of SY28/AI34. The idea, is even to choose among them (but again not linked to MVS), or to explore completely not showed one, and to produce a bibliographic study.

Assessment of part I

The mark related to this part of the project will count for **20%** of the overall project grade. You should preferably work in pairs to address the proposed project. A bibliographic report (maximum 5 pages) must be sent to: lounis.adouane@hds.utc.fr ; ghada.jaber@hds.utc.fr ; antoine.lima@hds.utc.fr and michael.mahamat@hds.utc.fr before **Friday 11/10/2024**, where it will be important to restore in the most synthetic and well-argued possible way (via for example commented equations and diagrams) the following points:

a) Section “Planning, control and decision-making for autonomous mono and Multi-Robot Systems (MRS)”
  1. Study and list the main existing control techniques to control the chosen cooperative CPS (one to two examples would be suitable).
  2. Understand how to explicitly explain how the perception/location/communication uncertainty impact the overall control of the studied CPS. The objective is to take into account these uncertainties in order to have most robust control and decision-making of the studied CPS.

b) Section “Localization of autonomous mono and MRS”
  1. Nature of sensors used for localization (e.g., GNSS) and the situations in which they are / or not relevant.
  2. What constitutes the system’s state (e.g., position, velocities) and how it is estimated (e.g., Kalman Filter) using the aforementioned sensors. In addition, study how

uncertainties are represented and how this information can be taken into account by the control aspect.

c) Section “Real-time communication and IoT of embedded systems”
1. The communication protocols used in cyber-physical systems.
2. The quality of service provided by the cyber-physical systems (delay, energy, reliability, packet loss, etc.).

Part II (Project): Navigation in formation of a group of cooperative mobile robots

As indicated previously, it is provided in this part of project a mini-software under Matlab containing elementary functionalities to control a Multi-Robot Systems (MRS), notably based on consensus-based control. This mini-software corresponds to the Robotarium[2], as already shown in the SY28/AI34 course. This mini-software allows both, to have an intuitive environment of simulation and also, which is of high interest, the possibility to perform remote experimentations with actual mobile robotics entities.

Assessment of part II

The mark related to this part of the project will count for **70%** of the overall project score. It will be necessary to provide a report in English between **5 to 10 pages maximum**, containing the most important points of your implementations and reflections/investigation (this report must be sent to all the SY28/AI34 teachers by email (cf. emails given in Part I) no later than **Friday 20th December 2024**). A 20 minutes defense is scheduled for on the **7th of January 2025** where it will be important to present the main obtained results with concise and well-argued manner.

The evaluation criteria for the final grade of this project are as follows:
- The level of implication (questions / interactions) of the student during the labs (**10%**);
- editorial quality of the report (**10%**);
- quality of the obtained results and relevance of the comments made in the report (**35%**);
- quality and clarity of the Matlab produced code (**25%**). A folder, containing all the Matlab code used to answer the questions. Do not hesitate to create a specific directory for questions requiring specific explanations, for example to answer question III.b, name the directory "Response_III_b".
- quality and degree of finalization of the questions marked with "*" (**20%**). Indeed, the questions with "*" are a little bit more complex / tedious to do than the others (in particular requiring more documentation).

I. Getting started

First of all, download the Matlab version of “robotarium-matlab-simulator-master” file from https://www.robotarium.gatech.edu/downloads. After going through the main components composing the available software, open and run first “*init.m*” (in the main folder) and after the Matlab script “*leader_follower_save_data.m*” (cf. Figure 4) available via the following relative path “\examples\data_saving”. It is important to highlight that in this simulation, the robots navigate under perfect conditions of localization and communication, and without hazards in the environment.

Sum-up the main steps of “*leader_follower_save_data.m*” script while using a flowchart. The flowchart should highlight the simple used function for localization and communication

[2] https://www.robotarium.gatech.edu/

between agents, as well the used control laws to ensure the stability of the navigation in formation of the group of mobile robots.

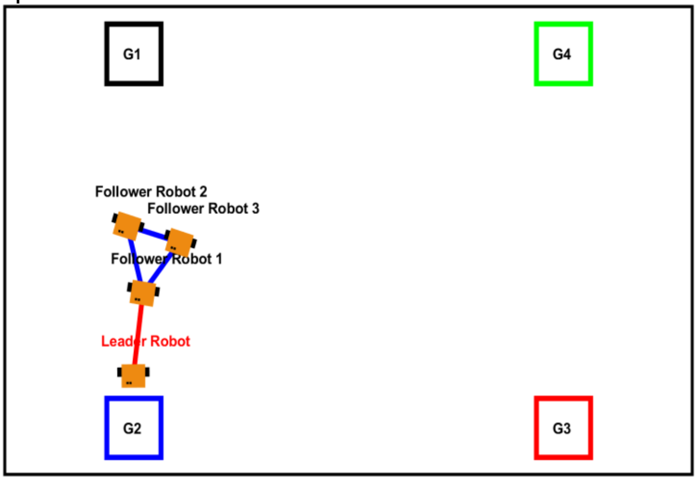

Figure 4. Navigation in formation of 4 mobile robots (1 leader and 3 followers in triangle formation). Robotarium simulation.

II. Main investigations

It is asked to answer the questions given below and to develop the functionalities requested in each subsection (control/planning/decision-making, localization and communication). The idea is at the end of the project to gather all the developed functionalities to have the most realistic simulated MRS, which contains an important number of parameters influencing the working of the studied CPS in real conditions. The aim is to obtain as robust as possible MRS under strict constraints (e.g., the geometric formation to maintain and the obstacles to avoid) and under uncertain localization and communications.

It is important to mention that once sub-section (II.a) has been completed, the idea is to try to have always reliable formation navigation even in the presence of uncertainties in the localization and the communication aspects. This will be done according to the developments requested in subsections (II.b) and (II.c).

a) Section "Planning, control and decision-making for autonomous mono and Multi-Robot Systems (MRS)"

1. In the available program "*leader_follower_save_data.m*", it is observed that the leader navigates from one waypoint to another while reaching first the position of the waypoint before performing the re-orientation maneuver. This strategy induces unsmooth navigation, propose an appropriate behavior to the leader in order to navigate between the waypoints with smother behavior (i.e., reach the assigned waypoint with already the appropriate orientation to reach the next waypoint, such as what is given in the SY28/AI34 course and in [9]).
2. We would like to have 4 followers navigating in symmetric diamond formation, where the added follower 4 will navigate behind Robot 2 and Robot 3 (cf. Figure 4). **This formation is the one which will be used in the remaining part of the project**.
   i. Define an appropriate rigid topology of the MRS to ensure the imposed geometric constraints of the targeted formation. Explain and highlight with appropriate simulations the efficiency of the proposed formulation.
   ii. Propose an appropriate metric to evaluate the level of precision to maintain the desired geometric formation. Explain.
   iii. While proposing other topologic configurations, show the importance to have indeed rigid topology to ensure these geometric constraints. This could be done for instance though some simulations highlighting the movements of the MRS in formation. It is

also suitable to use the proposed metric in (2.*ii*) to evaluate the level of reliability to reach and to maintain the targeted formation shape.

3. Between the waypoints, obstacles should be added in the environment (an indication will be given during the project). Propose an appropriate strategy of avoidance in order to guarantee the safety of the overall MRS in formation. Explain the proposed approach. Could you qualify it as reactive or as cognitive approach? Explain.
4. (*) Propose clear strategy showing a formation reconfiguration, from diamond shape to platoon formation and vice versa, according to the navigation context (for instance, as soon as an obstacle is detected, a platoon formation is privileged).
5. (*) Evaluate the importance of having precise localization and communication to guarantee the right working of the navigation of the targeted formation.

b) Section "Localization of autonomous mono and MRS" (only for FISE)

After a first version of the program in a), you are asked to perform the localization in a realistic way. For this purpose, the localization will be done in successive steps:

- *i.* Robots know their initial pose perfectly and evolve their own pose using a perfect odometer (no noise).
- *ii.* Simulate odometer noise and discuss how the pose uncertainty of each robot evolves with time.
- *iii.* Implement standalone observation of fixed landmarks: add landmarks to the simulation and make each robot estimate its own pose using odometry and perfect observations of landmark positions.
- *iv.* Simulate noisy observations and illustrate the loss of estimation quality that results from it.
- *v.* Make robots observe the position of each other and exchange their own estimated pose. Discuss how *cooperative localization* impacts the overall estimate.

1. For each case, you should study the accuracy and uncertainty of the localization procedure using error graphs and dedicated metrics.
2. (*) For the collaborative localization part, study the effect of imperfect communication on the state estimation (communication is lost between two robots).

c) Section "Real-time communication and IoT of embedded systems"

Concerning the communication task, you are asked to evaluate the level of Quality of Service (QoS) in terms of delay and reliability (packet loss rate).

Packets will be lost for example when the link between robots is broken (either the robot is not functional or it does not contain another robot in its communication range) or for example when there are obstacles between the robots.

For the delay, you will implement a function that calculate the delay of communication between robot when:

- *i.* The communication is perfect (no obstacle, no communication problem, …).
- *ii.* There is an obstacle (delay = delay+ Δ). Δ depends on how fast the robot will bypass the obstacle.
- *iii.* The communication link is broken; if the communication is not restored after 3s, the robot will display a message to say that it cannot re-establish the connection.

For the packet loss, you will calculate the number of packets lost due to the communication failures. Hence, for this part, it is required that you:

1. Implement the QoS criteria (delay and energy).
2. Study the reliability in terms of packet loss rate. For instance, at which level (e.g., 20%, 40% or 70%), this packet loss becomes critical for the system.
3. Change the MRS geometry and velocity (for example, set their desired distance to 3*actual distance) and study its impact on the communication in presence of obstacles.

Bibliography

[1], S. Wilson *et al*., "The Robotarium: Globally Impactful Opportunities, Challenges, and Lessons Learned in Remote-Access, Distributed Control of Multirobot Systems," in *IEEE Control Systems Magazine*, vol. 40, no. 1, pp. 26-44, Feb. 2020, doi: 10.1109/MCS.2019.2949973.

[2], J.M Vilca, L. Adouane and Y. Mezouar*, Stable and Flexible Multi-Vehicle Navigation based on Dynamic Inter-Target Distance Matrix,* IEEE Transactions on Intelligent Transportation Systems, vol. 20, no. 4, pp. 1416-1431, April 2019, doi: 10.1109/TITS.2018.2853668.

[3], Z. Zhu, L. Adouane, A. Quilliot, Flexible multi-unmanned ground vehicles (MUGVs) in intersection coordination based on ε-constraint probability collectives algorithm, International Journal of Intelligent Robotics and Applications, pp. 156–175, May 2021. https://doi.org/10.1007/s41315-021-00181-4.

[4], https://spectrum.ieee.org/swarm-of-robots-forms-complex-shapes-without-centralized-control, consulted on March 2022.

[5] Roumeliotis, Stergios I., and George A. Bekey. "Distributed multi-robot localization." *Distributed Autonomous Robotic Systems 4*. Springer, 2000. 179-188.

[6], Al Hage, J., Xu, P., Bonnifait, P., Ibañez-Guzmán, J. (2020). Localization integrity for intelligent vehicles through fault detection and position error characterization. *IEEE Transactions on Intelligent Transportation Systems*.

[7], Moiş, G., Folea, S., Sanislav, T., & Miclea, L. (2015, October). Communication in cyber-physical systems. In *2015 19th International Conference on System Theory, Control and Computing (ICSTCC)*.

[8], Jawhar, I., Al-Jaroodi, J., Noura, H., & Mohamed, N. (2017, June). Networking and Communication in Cyber Physical Systems. In *2017 IEEE 37th International Conference on Distributed Computing Systems Workshops (ICDCSW).*

[9], J.M Vilca, L. Adouane and Y. Mezouar, A novel safe and flexible control strategy based on target reaching for the navigation of urban vehicles. Robotics and Autonomous Systems, DOI 10.1016/j.robot.2015.01.008, volume 70, pages 215-226, August 2015.

[10], W. Ren, R. W. Beard and E. M. Atkins, Information consensus in multivehicle cooperative control, in IEEE Control Systems Magazine, vol. 27, no. 2, pp. 71-82, April 2007, doi: 10.1109/MCS.2007.338264.