Tutorials (*Travaux dirigés 2*), **multi-robot sub-part**
"Consensus based control"

Keywords: Multi-robot system (MRS), cooperative navigation, obstacle avoidance, consensus-based control, graph theory, Lyapunov stability.

I) Introduction

The main objective of this sub-part is to explore and understand more in details the consensus-based control. In addition to some MATLAB programs, you will use mainly the potentialities of Robotarium[1] [1] (cf. Figure 1) to answer to asked questions. This tool has been developed with MATLAB, and it would be easy to update the functions that you will develop in MATLAB in order to be used inside Robotarium simulator.

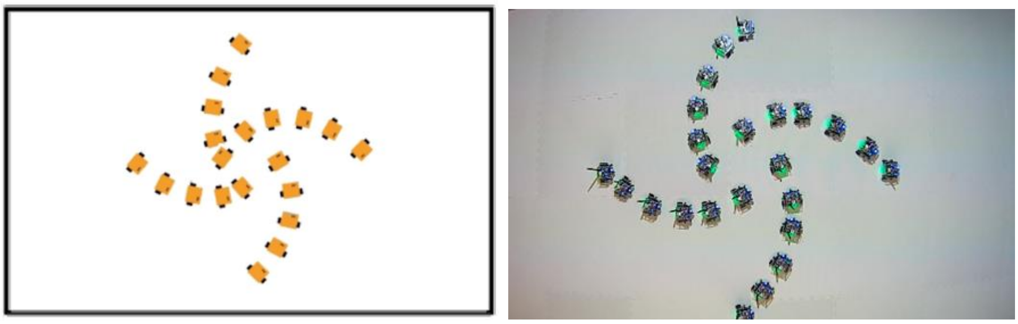

Figure 1. Robotarium simulation/experimentation. Time-lapse of robots' trajectories for a consensus-based control of 4 unicyles in cyclic communication network.

To carry out these tutorials, you will rely on the one hand on the followed SY28/AI34 lectures (sub-part cooperative navigation of MVS "Coordination of multi-agent system based on consensus control" chapter), and on the other hand on a set of MATLAB programs made available.

II) Tutorial's assessment

The assessment (which will contribute with 10% of the final mark of SY28/AI34 project) will be made on the basis of:

- The level of implication (questions / interactions) of the student during the tutorials/labs.
- An individual small report in pdf version, which summarizes the answers to the questions. You will need to justify your answers using in particular: analytical developments, graphics, tables and image captures linked to the carried-out simulations.
- 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".

You must return all the elements related to this tutorial, via a compressed archive

- Before 14th October for FISA.
- Before 21 October for FISE, since you have one more TD session (so more questions to deal with them).

The compressed archive must be sent by email to lounis.adouane@hds.utc.fr.

The evaluation criteria for the final grade of this tutorial depends on:

- editorial quality of the report;
- quality of the obtained results and relevance of the comments made in the report;
- quality and clarity of the MATLAB produced code;
- quality and degree of finalization of the questions marked with "*". These questions with "*" are a little bit more complex / tedious to do than the others (in particular requiring more documentation).

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

III) Consensus-based control for mixing arts and sciences

It is proposed in what follows to use the Robotarium simulator to apply the concepts seen in the course to produce a kind of MRS choreography, highlighting artistic trajectories of the MRS, corresponding to the results of mutual interactions of the mobile robotics entities. First of all, download the Matlab version of "robotarium-matlab-simulator-master" file from https://www.robotarium.gatech.edu/downloads.

a) After going through the main components composing the available software, open and run the MATLAB script "*consensus.m*" available via the following relative path "\examples\consensus_static". Sum-up the main steps of this script while using pseudocode or a flowchart.

b) This question as well as question (c) should be developed in a dedicated MATALB script that you will call "consensus_UTC.m" (it is to be noted that the developed script has to be used, in this initial study, without interaction with Robotarium software, so it will be a stand-alone script). Consider a group of 4 mobile robots, where each robot is modeled as a single-integrator dynamic. The state of each robot is defined as $\mathrm{X_i} = (\mathrm{x_i}, \mathrm{y_i}) \in \mathrm{R}^2, \mathrm{i} = 1, \dots 4$, and the control input of agent i is given by $\mathrm{u_i} \in \mathrm{R}^2$. The studied MRS has as initial positions $\mathrm{X_1} = (0, 2)$; $\mathrm{X_2} = (2, 0)$; $\mathrm{X_3} = (0, -2)$; $\mathrm{X_4} = (-2, 0)$.

   1. For each of the MRS topologies (as represented in Figure 2(a) and 2(b)) compute the corresponding Laplacian (***L$_a$*** and ***L$_b$***) matrix (while using Adjacency and Degree matrix).

Figure 2. **(a)** Fully connected topology **(b)** Cyclic topology

   2. For each topology given in Figures 2 (a) and (b), the convergence of the MRS toward the rendezvous position shown in one among of the Figures 3, 4 or 5. Attribute the right figure number according to the adopted topology. Explain summarily your answer.
   NB: This imply obviously that one of the figures given below does not correspond to any topology shown in Figures 2 (a) and (b). Identify it and try to find the actual topology corresponding to this last configuration.

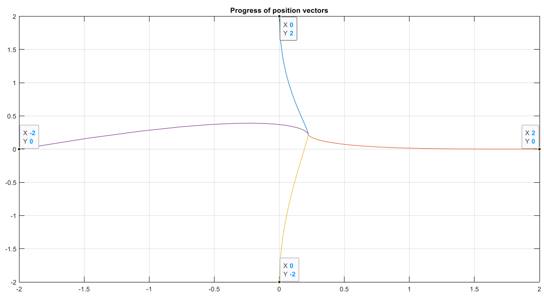

Figure 3

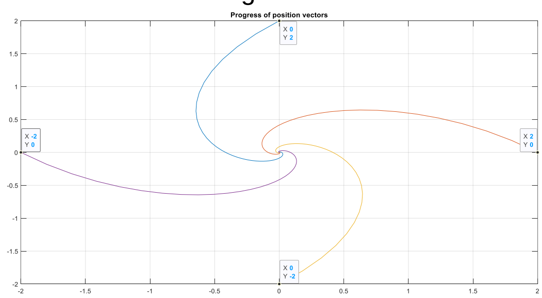

Figure 4

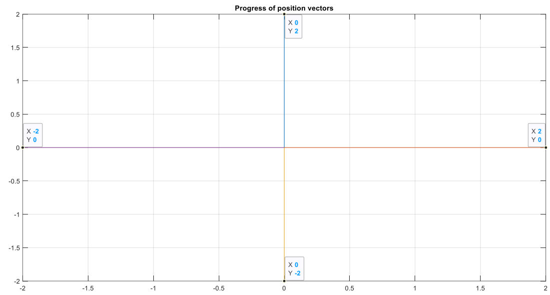

Figure 5

c) In this question, it is requested to developpe a sequence of appropriate parameters sequence of the used consensus-based control to obtain an **artistic motion** of the studied MRS which is composed of 8 agents (cf. Figure 6), modelled as single integrator (SI). To obtain the desired shapes, you can use among other things, the appropriate switch between:
   - Different MRS graph topologies (giving the communication link between agents), which means the use of different Laplacian matrices to define them.
   - Different convergence gains of the used consensus control to obtain different convergence speeds.
   - Different convergence behaviors (positive gains) and divergent behaviors (negative gains).
   - Different moments of the application time of each of the proposed above possibilities.

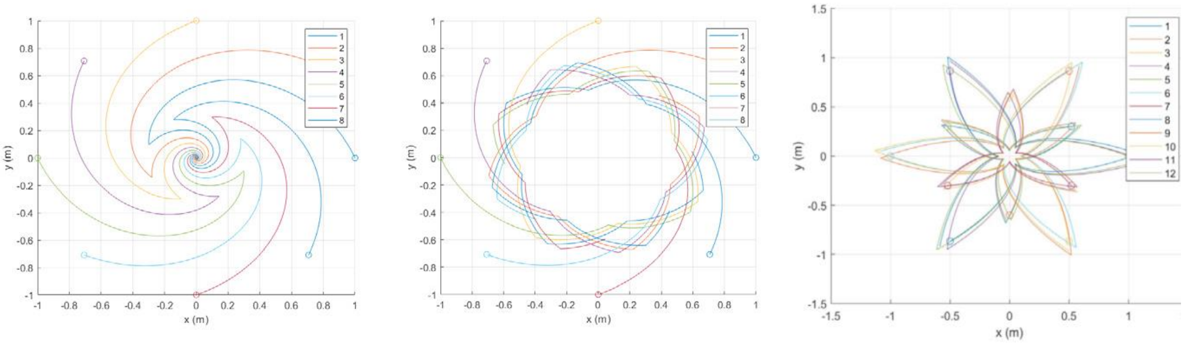

Figure 6. Some examples of artistic shapes obtained while using switched consensus-based control [2]

d) **(Only for FISE)** Once obtained the desired behaviors of the 8 agents, based on SI modeling, the idea is now to apply the proposed choreography on unicycles mobile robots.
   1. Update "*consensus.m*" in Robotarium software while rename it for example "*consensus_UTC_Bis.m"* and observe the obtained results. Plot the obtained results and compare it with regard to SI based model. Analyze and comment the obtained results.
   2. (*) In order to have more realistic results while using unicycle mobile robots, it is important that the robots do not collide between them. After studying the use of "*uni_barriers.m*" available via the following relative path "*\examples\barrier_certificates*", explain mathematically how Robotarium allows to avoid the collisions between the mobile robots.
   3. (*) Activate the obstacle avoidance behavior in "*consensus_UTC_Bis.m"* and plot the obtained results. Analyze and comment the obtained results. What you can propose to enhance the trajectories of the robots to obtain the desired movements?

References

[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], S. Bertrand, C. Stoica Maniu, C. Vlad, Teaching by Practice the Basis of Consensus for Multi-Agent Systems, IFAC-PapersOnLine, Volume 54, Issue 12, 2021, Pages 20-25, ISSN 2405-8963, https://doi.org/10.1016/j.ifacol.2021.11.004.