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Teaching by Practice the Basis of Consensus for Multi-Agent Systems

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Abstract: This paper provides in depth feedback on a new course on consensus for multi-agent systems developed for graduate students. The considered pedagogic approach gives a simple theoretical basis to the students through very few lectures while putting a strong effort into practice and applications. The paper describes how the transition to full remote teaching has been achieved due to the Covid-19 pandemic, especially regarding practical work sessions. Initially planed with aerial robots, practical work sessions have been modified to use a remote online platform for multi-robot experiments, *Robotarium* from Georgia Tech. To keep lectures and practical work sessions attractive to the students, especially in this remote learning context, a motivating example has been proposed to students, mixing arts and sciences, and consisting in re-creating a choreography from a kite contest video with a multi-robot system.

Keywords: Multi-Agent Systems, Consensus, Remote Laboratories.

1. INTRODUCTION

Numerous aerospace applications now involve Multi-Agent Systems (MAS) evolving autonomously to achieve their mission. Industry and research are therefore expecting from graduate students a suitable educational background in MAS modeling and control theory. Many Universities and Graduate Schools of Engineering propose curricula at Masters level related to MAS. They usually include topics such as design of system architectures (centralized, decentralized, distributed), graph theory, representation of dynamical systems, state estimation, control theory, etc.
Consensus algorithms for MAS is one of the topics that is generally taught to students. A large number of consensus-based algorithms have been developed by the research communities and have found numerous applications for aerospace systems, such as spacecraft formation control (Nazari et al. (2016)), multiple spacecraft attitude alignment (Xu et al. (2020)), alignment or formation control of aircraft (Hadi Rezaei and Bagher Menhaj (2018)) and Unmanned Aerial Vehicles (UAVs) (Wang et al. (2020a), Wang et al. (2020b)).
UAVs and aerial robotics are generally motivating subjects of interest to aerospace students, enabling to develop comprehensive applications for teaching and experiments in practical work sessions. Courses or MOOCs dedicated to modeling and control of a single robot or UAV (Bertrand et al. (2018), Bertrand et al. (2019)) usually receive a great interest from students. Therefore Multi Robot Systems (MRS) (aerial or ground) are also often considered application examples in MAS teaching.
This is the case of an elective course proposed to graduate students of CentraleSupélec, France, which deals with Multi-Agent Systems and applications to MRS formation control (Stoica Maniu et al. (2020), Stoica Maniu et al. (2019)). A part of this course is dedicated to consensus algorithms. The considered pedagogic approach is to teach students the basis of consensus theory for distributed control of MAS, while keeping a strong link to applications and practical implementation. Practical laboratory work sessions on swarms of Crazyflie Micro Air Vehicles (Preiss et al. (2017); Beuchat et al. (2019)) were initially intended to make students put into practice the theoretical notions from the lectures. However, due to the Covid-19 pandemic the teaching team had to ensure a quick transition to remote teaching. Transition to full remote education is a hard constraint and challenge for both teachers and students (Bojovic et al. (2020)) especially when dealing with practical laboratory work.
This paper provides in depth feedback on a new course on consensus for MAS given to graduate students, and more specifically on the pedagogical approach adopted to keep a strong link with practice and allow for experiments using an online open-access remote platform, *Robotarium* (Wilson et al. (2020)). This paper reveals a motivating example proposed to the students to be considered in practical work sessions and as a case study for further work. This example consists of re-creating a real choreography taken from a kite contest video by implementing consensus-based algorithms on a multi-robot system.

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Fig. 1. Experiment with three Crazyflie drones in the flight arena.

The paper is organized as follows. The next section details the content of the lectures. Section 3 presents the approach adopted for practical work sessions through an example. Section 4 describes a motivating example provided to the students in practical work sessions to be continued as a case study in semi-autonomous work by the students, quite similar to Project-Based Learning. Finally, the last section is devoted to some concluding remarks and directions of improvements.

2. CONTENT OF THE COURSES

Several lectures on consensus are given in two different modules at CentraleSupélec, for second year and third year graduate students (equivalent Master level).

2.1 Second year module

A simplified approach is proposed for the second year students during the elective course on "Dynamical Multi-Agent Systems. Application to drone formation control", with basic automatic control and optimization background. Indeed, the students have knowledge on PI/PID control, lead-phase control, cascaded control, feed-forward control and state-feedback. This course offers the possibility to address a complex system (i.e. MAS) in a simple way, easy to understand and to implement.

The 35-hours class time elective course is divided in interactive lectures (18 hours), practical sessions (6 hours), case studies (9 hours) during which students work in small groups, followed by practical experimental work and assessment (2 hours). The practical work sessions were initially planned in an indoor flight arena (see Figure 1). However, due to the Covid-19 pandemic, they were replaced by remote experimental tests using the *Robotarium* platform for multi-robot systems developed by Georgia Tech.

At the end of this course, students are capable of: (i) performing dynamic modeling of a quadrotor UAV, a ground mobile robot, and a Multi-Agent System, (ii) designing different control laws for UAVs (consensus-based control, feedback linearization control, backstepping control, control by saturation functions), (iii) using path/trajectory generation and tracking methods and (iv) implementing consensus-based control techniques for MAS and swarm control based on behavioral rules.

The proposed lectures and tutorials on consensus (9 hours class time) start with modeling approaches and tools for MAS like simplified models for control design, reference frames and motion analysis associated to MRS applications, and graph theory notions. Then, consensus algorithms for distributed control are presented. Continuous-time and discrete-time algorithms are presented for distributed control of MAS with single integrator dynamics. The problematic of communication reduction by event-triggered strategies is also introduced. In addition, algorithms for cooperative control of MRS are addressed (leader-follower, consensus, behavior-based-rules, formation tracking displacement / distance-based algorithms), and some extensions to non-rigid formation are discussed. The pedagogical approach is meant to present consensus-based algorithms that are rather easy to understand through simple, practical examples while making students aware of the concerns related to their implementation. These algorithms are applied to control MAS with simplified dynamic models and different communication topologies during the two practical work sessions. The algorithms are then used for the formation control of MRS. Finally, the Matlab scripts are adapted for the remote experimental tests on the online *Robotarium* platform (see Section 3).

For the case study, the students work in small groups. Each group has to propose a subject related to the module content in the context of a practical application. The students can use the examples presented during the practical work sessions as a start point for their case study. During the first occurrence of the course in 2019-2020, the following consensus-subjects have been proposed:

- *Sheeps and Shepherds*, *Chase the Rat*: Surrounding drones to limit their escape.
- *Saving the President*: Surrounding one vehicle and protecting it.
- *Building Evacuation*: Evacuating humans in case of fire.
- *The Greta Project*: Cleaning up oceans with marine drones.
- *Alphabet*: Using drones to write messages.

There are three sessions (9 hours class time) for the case study during which all groups are working under the supervision of the pedagogical team. Each group has to prepare a written report, present the obtained results in an interactive poster session, and evaluate the work of the other groups by filling in a survey (peer evaluation). The final grade is obtained from the report evaluation and the interactive poster evaluation.

2.2 Third year module

A more in depth consensus lecture is proposed in the module "Control architectures of complex systems" to the third year students (equivalent Master level) in Control Engineering.

This module addresses modeling and control of complex systems, and more precisely decentralized, distributed, hierarchical strategies. Model predictive and consensus-based control techniques are presented within this scope with the conditions to achieve the performance level of centralized control taught in other courses, while keeping a reasonable computation load (7.5h lectures).

The lectures devoted to consensus (3h) start with some

reminders on the basic algorithms for MAS with single integrator dynamics, as seen in the second year module. An extension to non-linear Euler Lagrange dynamics is then presented. The chosen algorithms (Ren (2009)) are simple in their formulation while enabling to provide stability guarantees for the closed loop MAS. To account for implementation concerns to physical systems, control laws accounting for actuator saturation are presented. A distributed state estimation algorithm based on consensus is proposed to the students for a simple linear system and compared to a centralized estimator on a network with three sensors.
Tutorials (7.5h) and case studies (6h) are also proposed to the students with the same pedagogical approach as for the second year module.

3. PRACTICAL WORK SESSIONS

Practical work sessions concern the direct application of consensus algorithms for distributed control of Multi-Agent Systems and extension to formation control of Multi Robot Systems. For the different exercises proposed in these sessions, the pedagogic approach is divided into three steps, each of them associated with Matlab scripts to be completed by the students:

- definition of the communication graph of the MAS, design of the control law for two-dimensional agents with Single Integrator (SI) dynamics and validation by simulation (Matlab script "SImularium").
- application of the control law in simulation to mobile ground robots with Differential Drive (DD) kinematics (Matlab script "RobotariumSimu").
- remote experiment on real robots using the *Robotarium* online platform (Matlab script "Robotarium-Expe").

These three steps are detailed in the next subsection and illustrated through a simple exercise consisting in implementing a distributed consensus control law.

3.1 Step 1: control law design for the MAS

In the first step, students have to define the communication graph to be used and design a distributed control law for a MAS composed of two-dimensional agents with single integrator dynamics. The graph and the control law have to be coded in Matlab scripts prepared by the teaching staff and named SImularium. These SImularium scripts have been created to reproduce the same structure as the scripts used by the online platform *Robotarium* for experiments but to simulate the behavior of a MAS with Single Integrator dynamics. It generates plots of agents' trajectories and the time evolution of their states and control inputs.

Consider as an example the consensus algorithm

$$\dot{x}_i(t) = u_i(t) = k \sum_{j \in \mathcal{N}_i} a_{ij}(t) \left(x_j(t) - x_i(t)\right) \qquad (1)$$

where $x_i \in \mathbb{R}^2$ and $u_i \in \mathbb{R}^2$ are the state vector and control input of agent i of the MAS ($i = 1, \ldots, N$), and where $\mathcal{N}_i$ is the set of its neighbor agents. The coefficient $k > 0$ is some scalar gain. The scalar weight a_{ij} corresponds to the i, j-term of the adjacency matrix A associated to the communication graph of the MAS and it is chosen equal to 1 if agent i is able to get information from agent j. Otherwise, it is set to zero. By convention, $a_{ii} = 0$. Simulation results provided by SImularium are illustrated in Figure 2 in the case of $N = 4$ agents and a communication graph defined by a directed ring. The students are invited to investigate the influence of the communication topology by implementing several types of graphs, computing their algebraic connectivity (2^{nd} eigenvalue of the Laplace matrix associated to the graph) and comparing the convergence speed to the consensus and the trajectories of the agents.

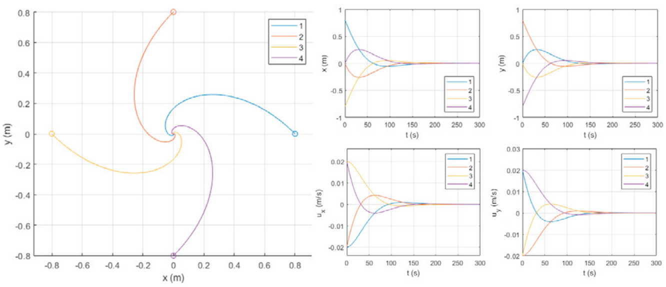

Fig. 2. Step 1: simulation with SImularium (single integrator dynamics) - Example of consensus with $N = 4$ agents

3.2 Step 2: simulation on a MRS

Once Step 1 has been validated, control laws implemented in SImularium can then be copied inside RobotariumSimu scripts and tested by the students.
RoborariumSimu scripts have been prepared by teachers in order to add plotting capabilities to *Robotarium* scripts. They simulate the trajectories of ground mobile robots in closed-loop behavior. Differential Drive kinematics are used for the simulation, while the control law has been designed considering a simplified SI dynamics for position control. The simulation, therefore, accounts for a transformation from a cartesian velocity control input (outer control loop on position) to linear speed and orientation reference for the robot. An orientation controller is also used (inner control loop on orientation). This process is very well explained in the *Robotarium* documentation and in Wilson et al. (2020). It is of pedagogic interest for aerospace students since it reproduces the same type of hierarchical control design as for guidance and control of aerospace vehicles.
Students can therefore learn that control design may be done by considering a simplified dynamic model, while validation and performance analysis must be done considering the full model of the vehicle.
Examples of plots generated by RobotariumSimu for the simple consensus algorithm (1) are presented in Figure 3. Students are invited to analyze differences from the previous results and find explanations. Due to inner loop control and orientation closed-loop behavior, the resulting closed-loop trajectories of the robots are indeed different from those of SI agents. In addition, Robotarium implements a function that modifies the control input of the robots to avoid collision between them and with the borders of the arena. In this example of algorithm (1), asymptotic consensus can therefore not be obtained since the robots

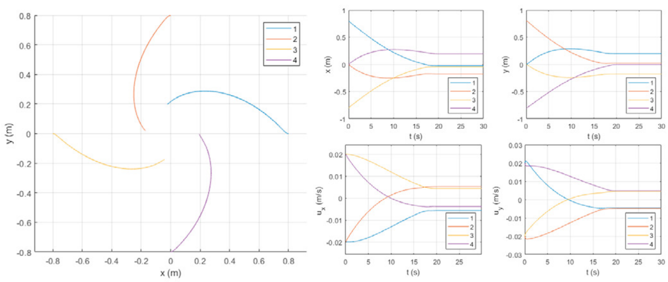

Fig. 3. Step 2: Simulation with *Robotarium* (mobile robot dynamics) - Example of consensus with $N = 4$ agents.

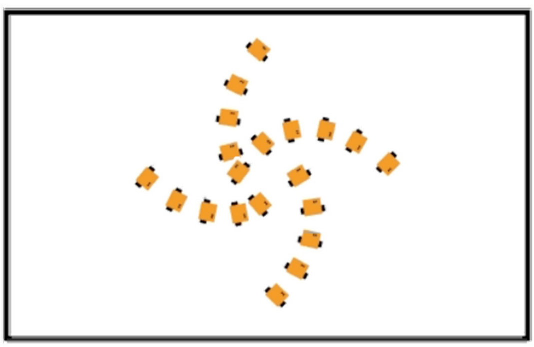

Fig. 4. Step 2: Simulation with *Robotarium* (mobile robot dynamics) - Timelapse of robots' trajectories for the consensus example with $N = 4$ agents.

stop before colliding. Agents are not single points, but dimensions of the vehicles are accounted for, as shown on their simulated trajectories (Figure 4).

3.3 Step 3: remote experiments on real robots

The last step consists in submitting a RobotatiumExpe Matlab script as online experiment on the *Robotarium* website. No modification on the implemented algorithm is required from the students compared with the previous steps, excepted some parameter tuning. Indeed, a multiplicative gain should be included in the control law of (1) to be able to set the speed of the robots accordingly to physical limitations and in compliance with the tracking performance of the orientation controller.
Figure 5 shows the results obtained from the experiment. As it can also be noticed on the trajectories of the real robots (Figure 6), the behavior of the real MRS is really close to the one simulated during the previous step. Experimental data and a video of the experiment can be downloaded by the students from the *Robotarium* website which is greatly appreciated as a good substitute to physical experiments in this pandemic period.

Note that, for all the proposed exercises, the choice of agents with two dimensional dynamics also enables the students a very intuitive and easy transition to the application of control of mobile ground robots, as offered by *Robotarium.*

4. A MOTIVATING EXAMPLE AS CASE STUDY: ARTISTIC CONSENSUS

After practical work sessions, the students have to work on case studies to put further into practice consensus

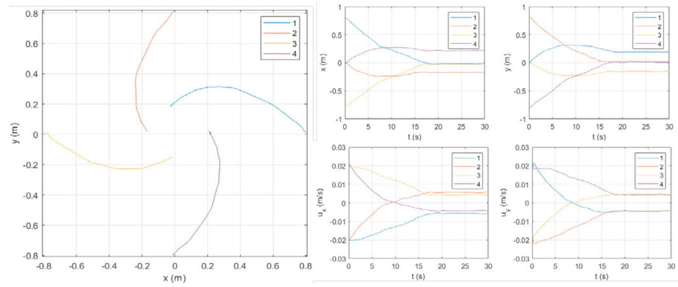

Fig. 5. Step 3: Experiments with *Robotarium* - Example of consensus with $N = 4$ agents.

Fig. 6. Step 3: Experiments with *Robotarium* - Timelapse of robots' trajectories for the consensus example with $N = 4$ agents.

algorithms. More complex applications are to be considered and imagined by students. An example of application proposed to the students, mixing Control Engineering and Arts, is detailed in this section.

4.1 Artistic pattern generation with Multi Agent Systems

In STEAM (*Science Technology Engineering Art Math*) Education, Arts is seen as an additional motivation for students to learn Control Engineering. Examples of mixing arts and control can be found in the robotic and control research communities, e.g. artistic pattern generation using ground robots (Alonso-Mora et al. (2011)), trajectory generation and motion synchronization for choreography and artistic patterns using UAVs (Dinh et al. (2017), Du et al. (2019)). Geometric pattern formation with double integrator agents have also been considered in (Moses et al. (2018)) as well as consensus algorithms for artistic pattern generation in MAS (Tsiotras and Reyes Castro (2013), Tsiotras and Reyes Castro (2014)).
Some of these works can be source of inspiration to educational applications. In the continuity of the pedagogy developed for the lectures and practical work sessions, a simple approach has been chosen. It consists in making the students start from a basic consensus algorithm such as the one in (1) and make them propose changes on the way to define and modify, with respect to time, the gains and the communication topology of the MAS to get artistic patterns for the agents' trajectories.
As an example, patterns of Figure 7 have been obtained using (1) with $N = 8$ agents and considering a directed ring communication topology. Combinations of basic operations on the adjacency matrix (transpose) and on the gains (change of sign) along with choice of the switching

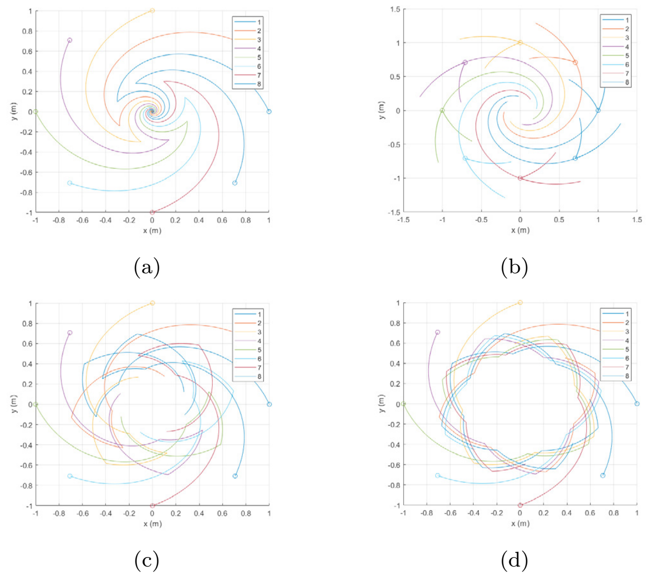

Fig. 7. Example of artistic patterns obtained by consensus for a MAS with $N = 8$ agents.

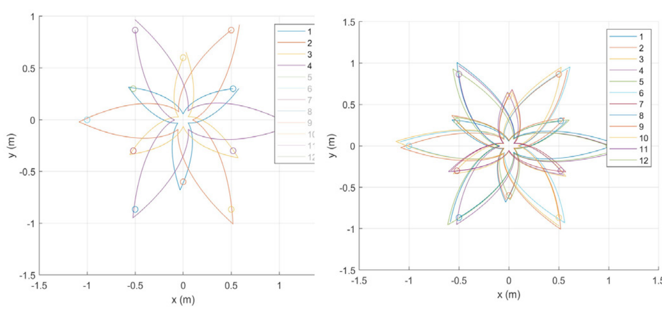

Fig. 8. Artistic patterns obtained by the students

instants lead to these different artistic patterns.
Another example of artistic pattern obtained by the students themselves is the flower or mandala-like geometry represented in Figure 8, for $N = 4$ agents (left) or $N = 12$ agents (right).

4.2 Case study: kite choreography

A motivating example has been proposed to the students as part of practical work sessions and as a basis for a case study. It consists in reproducing with a MAS a sequence of choreography from a kite contest video found be the students themselves. This video sequence shows six kites performing a cyclic pursuit with changes of direction and circle radius. It is given to the students with the instruction of reproducing the same choreography with a MAS and *Robotarium*. Students have to follow by themselves a control design approach, that can be summarized by the flowchart of Figure 9. The kite choreography can be reproduced by a MAS of $N = 6$ agents and a distributed consensus control algorithm by considering a communication topology modeled as a directed graph. Changes of directions of the agents are obtained by triggering changes in the direction of the arcs of the graph. Changes in the motion radius are obtained by switching between a stabilizing control law ($k > 0$ in (1)) and a destabilizing one ($k < 0$ in (1)).

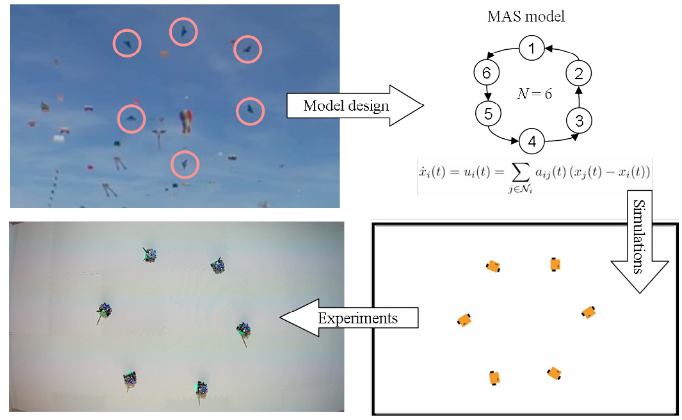

Fig. 9. Flowchart of the control design approach

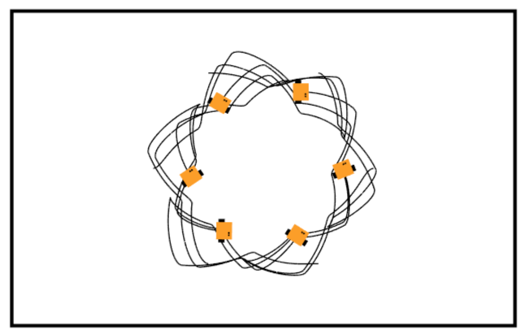

Fig. 10. Kites' choreography simulated with *Robotarium*

An example of resulting trajectory for the MAS is presented in Figure 10. A video is also available at `https://youtu.be/zt1KCOs8UK4` which shows the selected sequence from the kite contest and the choreography obtained with the simulated MAS and real robots from experiments with *Robotarium*.
This kite contest example motivated some of the students to work on case studies mixing MAS control and arts, and also gave them the idea to look at other examples of choreography from different domains such as synchronized swimming.

5. STUDENTS' FEEDBACK

Feedback from the students has been very good. Some of their comments are given below:

- "Thank you very much for all the course! The course was really interesting and I was really passionate by the subject."
- "An exciting elective course, very interactive, with dynamic and involved teachers, and open projects that allow us to apply the concepts learned during the lecture."
- "Interesting tutorials and adequate scientific level."
- "The best part is that what is learned is directly applied during the tutorials."
- "The experimentations on *Robotarium* reinforce the theoretical notions."

This feedback confirmed the chosen pedagogical approach with strong link to applications and practice.

6. CONCLUSION

This paper has presented in depth feedback on a new course on consensus for multi-agent systems developed for graduate students at CentraleSupélec, France. A strong effort has been put on applications and practice. Due to the Covid-19 pandemic, transition to remote teaching has been made and experiments initially planed with aerial robots have been changed into remote experiments with the online platform *Robotarium*.
Some examples illustrating the pedagogical approach have been presented as well as a basis for a case study proposed to the students, considering artistic consensus.
Due to transition to full remote teaching, labs on aerial robots have been replaced by a demonstration done by teachers on the implementation of distributed consensus control laws for Crazyflie drones in the flight arena of CentraleSupélec. Future work will be done to allow inperson or remote labs for the students on the drones.

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