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# Enthusing engineering students over multi-agent systems control via human-robot interaction

V. Petit-Magat<sup>1</sup>, H. Lhachemi<sup>1</sup>, C. Stoica<sup>1</sup>, A. Thakker<sup>1</sup>, M. Da Silva<sup>1</sup>

**Abstract**—This paper reports an easily reproducible experiment that can be used in class to illustrate fundamental concepts on Multi-Agent Systems (MAS) via human-robot interactions. In this context, the primary objective of this paper is to provide teaching resources to motivate students taking engineering courses on Robotics and MAS control that involve humans in the loop interactions. A leader-follower approach with a human being as a leader and a 4-degree of freedom robotic manipulator as a follower is proposed. An illustrative video is provided to highlight the first experimental results. Furthermore, the proposed experiments are further intended to popularize Robotics and Control to broad public during Open Days events in universities.

## I. INTRODUCTION

It is now well established that improved motivation and learning efficiency can be reached via game-like approaches; this is particularly true in the field of teaching by involving the students in an entertaining way [12], [7]. Macro Robotics is a perfect fit for this approach because it is a human-observable physical system with ease of interaction. Moreover, Robotics is an interdisciplinary science that can illustrate many domains, ranging from Engineering to Mathematics or to Neuroscience. In this context, the term *Educational Robotics* began to emerge to designate robots used for teaching purposes. The authors of [4] promote some events undertaken by the University of Almeria (Spain) to attract pre-university students towards Robotics. The paper [11] also presents several entertaining workshops with robots to introduce the fundamentals of Robotics to children and teenagers. It is worth being noted that, in the recent years, numerous robots have been specifically designed for interacting with children and scholars (e.g., ChildBot robot [3], Nao robot [16], [5], EduRobot [2]). The primary objective of this trend is to increase the interest of young generations for Robotics and the related scientific fields [11].

Teaching Robotics and Control fundamentals, including human-robot interactions, is nowadays a fundamental component of university engineering curricula [13], [8], [16]. The newly deployed curriculum of CentraleSupélec<sup>1</sup> [6] offers the possibility to develop new teaching modules at the forefront

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<sup>1</sup>CentraleSupélec is one of the most notable French graduate engineering schools, called "Grandes Ecoles", with a very selective entrance exam.

of research and based on innovative pedagogical approaches. In this context, new courses on the control of Multi-Agent Systems (MAS) with applications on mobile robots and drones are proposed at CentraleSupélec [14], [1], [9]. A possible option for enlarging the range of application of these modules is to propose to the students human-robot interactions case-studies using the existing experimental platforms.

This paper reports a new laboratory case study to illustrate fundamentals on Control of Multi-Agent Systems involving human-robot interactions. The experiment includes a robotic arm that follows the trajectory of a human hand. The aim of this case study is to illustrate theoretical concepts on leader-follower approaches within a human-robot interaction framework. Robotics experiments often require either numerous hardware/software tools (e.g., additional sensors) or a lot of time to develop a precise setup. Hence, they are both expensive and time-demanding, making them difficult to put in place in the context of a teaching module. The main advantage of the approach reported in this paper is that it offers an easily reproducible robotic setup which requires a low-cost<sup>2</sup> open-source robotic arm and a low-cost webcam. On top of that, the proposed experiment does not require a sophisticated and precise setup and does not monopolize a lot of space. A video illustrating the experimental setup is available at the following link [https://youtu.be/xCWzX\\_alrdg](https://youtu.be/xCWzX_alrdg).

The paper is organized as follows. The overview of the teaching module is proposed in Section II. Section III focuses on the theoretical aspects. Section IV presents the experimental setup. Section V presents the results of the experiments. Finally, concluding remarks as well as further perspectives on its use for educational purposes are formulated in Section VII.

## II. MODULE OVERVIEW

One elective teaching module on *Control of dynamical Multi-Agents Systems* (35h onsite) is offered for the second year students of CentraleSupélec. This course is composed of interactive lectures, tutorials, and a case study organized as a Problem Based Learning (PBL). More details on the scientific content of the course are provided in [14], [1], [9]. The objectives of the course are ambitious as the aim is to make students with elementary notions on Control Systems<sup>3</sup> discover advanced control techniques by means of experimentation on multi-vehicles (e.g., ground vehicles, drones, etc.).

<sup>2</sup>The robotic arm used in this experimentation is 10 times less expensive than classical robotic arms used for research goals.

<sup>3</sup>The targeted students for this module have only basic notions in Control (P/PI/PID, phase-lead, feed-forward, cascaded, and state-feedback control coupled with a Luenberger observer).

In order to enlarge the application field and to attract more students, one idea is to *enrich the mobile robotics applications with human-robot interactions* in the general framework of Multi-Agent Systems Control.

Regarding the case studies, the students (working in small groups) propose a scenario<sup>4</sup> on Multi-Agent System Control. Then, after a state-of-the-art phase, they formulate the problem and propose solutions based on leader-follower or consensus-based control techniques taught in this module. An important part of the case study is dedicated to implementations on experimental platforms. A poster session is organized at the end of the module. Students are evaluated based on their results exposed during the poster session and based on the report provided at the end of the course.

The existing experimental platform at CentraleSupélec used for this teaching module includes an OptiTrack motion capture system, together with several ground and aerial vehicles, such as TurtleBot3 Burger and TurtleBot3 Waffle Pi ground vehicles, Crazyflie drones, etc. To allow more elaborated experimental scenarios, compatible robotic arms OpenMANIPULATOR-X were recently acquired. These robotic arms can be used either independently (anchored on a rigid plate) or mounted on a mobile TurtleBot3 Waffle Pi ground vehicle. The main purpose is to enlarge the Multi-Agent Systems applications on mobile robotics including collaborative robotics and human-in-the-loop. An intuitive experiment based on human-robot interaction using a leader-follower approach is proposed in this paper. This lab experiment is intended as a starting point for future case studies, allowing students to better understand the tuning procedures for leader-follower control laws, while offering wider perspectives with respect to the case study scenarios.

### III. THEORETICAL FOCUS

The laboratory experiment reported in this paper consists of a standard leader-follower problem. We detail here the proposed approach.

#### A. Leader-follower approach

The main goal is to control the position of a given number of mobile robots such that the “follower” vehicles pursue the “leader”. The leader can be one of the robots or a virtual point that moves in a predefined workspace. The other robots are the “followers”. They aim at remaining at a chosen distance from the leader. In this approach, only the relative position of the follower compared to the leader matters as the follower robots do not consider their mutual positions.

In the proposed experiment, a leader-follower control law with single integrator dynamics has been considered. Here,  $x_0(t)$  and  $x_i(t)$  represent the position of the leader and of the followers at time  $t$ , respectively, while  $u_0(t)$  and  $u_i(t)$  are their respective velocity. The reference trajectory of the leader

<sup>4</sup>The subjects proposed by the students are mainly inspired by actual environmental and societal challenges (e.g., cleaning up oceans with marine drones, evacuating humans in case of fire/Earthquake, precision agriculture, nuclear waste storage and disposal, etc.).

is denoted by  $x_0^*(t)$  and the reference positions with respect to the leader to be tracked by the followers are denoted by  $r_{i0}^*(t)$ . The current distance between the leader and the follower  $i$  is  $r_{i0}(t) = x_i(t) - x_0(t)$ .

The implemented control law ensuring that the leader tracks the desired trajectory is given by:

$$u_0(t) = -k_L \cdot (x_0(t) - x_0^*(t)) + \dot{x}_0^*(t), \quad (1)$$

where a gain  $k_L > 0$  is considered for the leader.

However, in the proposed experiment, the leader is the human hand. Therefore, it does not follow any specific desired trajectory nor any control law. It indeed moves freely under the will of the experimenter.

On the other hand, a control law is needed to guarantee that the position of the follower, which is the robotic arm, remains to a chosen distance from the leader. In this setting,  $\epsilon_{i0}$  represents the tracking error of the follower robot  $i$  with respect to the leader:

$$\epsilon_{i0}(t) = r_{i0}(t) - r_{i0}^*(t) = (x_i(t) - x_0(t)) - r_{i0}^*(t). \quad (2)$$

The control law of the follower  $i$  that ensures the closed-loop stability of the tracking error dynamics is:

$$u_i(t) = -k_F \cdot ((x_i(t) - x_0(t)) - r_{i0}^*(t)) + \dot{x}_0(t) + \dot{r}_{i0}^*(t), \quad (3)$$

with the follower gain  $k_F > 0$ . Indeed, it can be easily observed that this control law ensures the following error dynamics:  $\dot{\epsilon}_{i0}(t) = -k_F \cdot \epsilon_{i0}(t)$ , which is exponentially convergent as soon as the gain  $k_F$  is positive. In this case, the control law ensures that the relative distance between the leader and the follower tends towards the desired value.

#### B. Human-robot interaction

Leader-follower-based control laws are an example of control strategies applied amongst robots to enable them to move in formation. However, in order to capture the attention of the students and increase their interest in this class, it was decided to create an experiment relying on a human-robot interaction. Therefore, the student is directly involved in the loop as his/her hand becomes the “leader”. The hand position is tracked by a camera and sent to the robot, which is the “follower”; the robot is therefore able to follow the human hand and reproduce its trajectory. This enables an intuitive and convenient interaction with the robotic arm.

For safety reasons, the robot should remain at a reasonable safety distance of the human hand. This distance can be enforced through the “reference distance”  $r_{i0}^*$  provided to the leader-follower control law as described in Section III-A.

## IV. CASE STUDY

#### A. Experimental setup

In order to access the position of the human hand, several approaches can be used. The most common one consists of placing sensors directly on the hand of the human. However, since the goal of this experiment is for teaching purposes, the proposed setup must be easily reproducible, even without specific material such as position sensors. Therefore, an

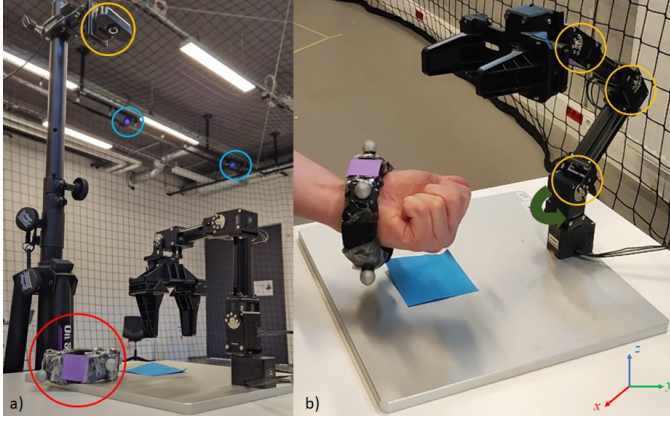


Fig. 1. a) Layout of the hardware used during the experiment (left), b) Experimental setup and degrees of freedom (highlighted in yellow and green) of the OpenMANIPULATOR-X (right)

object detection approach has been adopted. In our setting, a colored marker placed on the hand of the subject is detected by a camera (e.g., a webcam) positioned above the workspace of the robot. Figure 1.a depicts the layout of the objects used during this experiment, namely: the robotic arm OpenMANIPULATOR-X, the webcam (encircled in yellow), and the bracelet (encircled in red) used to place the purple marker on the hand of the user.

The blue marker, placed on the platform of the robotic arm, is used for the calibration of the camera. More precisely, the calibration algorithm compares the detected image of the blue marker with its actual size (used as an input of the algorithm) for determining the position of the camera. This approach enables an easily reproducible experiment (with a 15min setup) because the camera does not need to be always at the exact same place for ensuring good experimental results.

It is worth being noted that image distortions can induce large errors, hence jeopardize the tracking performances. Therefore, as a preliminary step, distortion coefficients of the camera can be estimated (if they are not provided by the manufacturer) and considered in the calibration process.

Once the calibration is completed, the camera detects a purple marker placed on the bracelet around the user's hand (see Fig. 1.b). The implemented algorithm computes the position of the hand of the human, that is the "leader" position. This position is sent to the robotic arm so that the "follower" can track the "leader" position. This setting is depicted by Fig. 1.b.

### B. Hardware

The proposed experiment is performed with a robotic arm OpenMANIPULATOR-X from *Robotis*. This robotic arm is made of 4 articulations, 3 of them being cuboids (encircled in yellow in Fig. 1.b) and the last one being the gripper. These articulations are arranged in an open-loop kinematic chain. Therefore, the robot has 4 degrees of freedom, all of them being rotation joints, 3 of them along the same axis  $y$ , and one being along the  $z$  axis (see Fig. 1.b). The axes  $x$ ,  $y$  and  $z$  have

been chosen by the designers of the OpenMANIPULATOR-X so that the  $x$  axis is in front of the robot, the  $y$  axis on the side, and the  $z$  axis defines the height of the end-effector. The word "end-effector" designs here the center of the gripper. This is the point considered as the "follower" is the leader-follower control law. It is possible to open and close the gripper of the arm in order to catch an object. However, it is impossible to rotate the gripper as there is no rotation actuator along the wrist. This is not an issue in our experiment because only the position of the end-effector is controlled, not its orientation.

The used camera is a WEBEE Webcam USB Full HD 1080P 2M Pixels Autofocus. This camera was chosen in our setting because it offers satisfactory characteristics and resolution for our purpose while being affordable.

This experiment only requires one single computer as long as it has two USB ports (the robotic arm can be connected to the computer via a U2D2 card). The robot is manipulated using ROS (Noetic version) and data are extracted from the camera using OpenCV and Python. Notice that all the equipment can be installed on a single table.

### C. Identification of the hand position

As described in Section IV-A, a purple colored marker is placed on the hand of the user in order to track its position. The identification of the purple marker's position is done by using a calibration phase. This calibration phase is important as it links the data received by the camera to data that can be used by the robotic arm. Two information are extracted from this phase. First of all, the pixel corresponding to the center of the blue marker (called the *calibration marker*) on the image is matched to its position in the workspace of the robot, which will be used to find the  $x$  and  $y$  positions of the hand during the experiment. Then, since the size of the marker is known, the size of a pixel is estimated. This data is used to find the height  $z$  of the hand.

Once the calibration is completed, an other smaller marker (purple during this experiment) is put on the hand of the user so that the camera can track its position. The use of a bracelet to place the marker is also possible as it is more convenient to switch from one user to an other one.

To deduce the position of the hand from the image captured by the camera, the first step is to determine the size, in the real world, of a pixel captured by the camera. Indeed, as the hand may move closer or further from the camera, the size of the area captured by a pixel changes. This value can be deduced by knowing the real size of the considered marker and the number of pixel corresponding to the marker on the image. This approach is the one applied during the calibration phase.

To find the position  $(x, y)$  of the marker, the field of view of the camera must be linked to the workspace of the robot. This means to match the position of a pixel on the image to a position in the workspace of the robot. This process can be performed thanks to the calibration phase. Figure 2 shows the workspace of the robot and its frame (in red color), the field

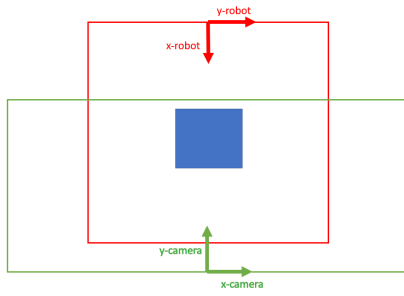


Fig. 2. Workspaces of the robotic arm and the camera

of view of the camera and its axis (in green color), and the blue marker used for calibration.

Let us denote by  $(c_x, c_y)$  the position of the center of the marker in pixel (in the frame of the camera). Since the position of the center of the calibration marker (blue color) is known, both in the frame of the camera (i.e.,  $(c_{x_{cam}}, c_{y_{cam}})$  found in the calibration phase) and in the workspace of the robot (denoted by  $(o_x, o_y)$ ), we can deduce the position of the marker  $(p_x, p_y)$  in the workspace of the robot:

$$\begin{aligned} p_x &= o_x + \delta_p \cdot (c_y - c_{y_{cam}}) \\ p_y &= -o_y + \delta_p \cdot (c_x - c_{x_{cam}}) \end{aligned}$$

with  $o_x$  the offset on the  $x$ -axis,  $o_y$  the offset on the  $y$ -axis, and  $\delta_p$  the size of the pixel.

To find the position  $z$  corresponding to the height of the marker, the size of a pixel on the current image is compared with the one found during the calibration procedure. This can be completed, by noting that there is a proportionality relationship between the size of a pixel and the distance between the marker and the camera:

$$\delta_p \cdot d_{cam} = \text{constant}$$

with  $d_{cam}$  the distance to the camera. Since the distance between the camera and the marker used during the calibration phase is known, the current distance can be found using a cross product. Then, this value needs to be subtracted from the distance between the camera and the ground of the robot ( $z = 0$ ) to find the height of the hand.

The difference of position between the human's hand and the end-effector of the robot is then used to compute the velocity of the robotic arm.

## V. RESULTS

### A. Reproducing the trajectory of the human hand

This section aims at assessing the performance of the reported experiment on the OpenMANIPULATOR-X. In a first step, the position of the purple colored marker detected by the webcam (deduced with an image processing algorithm) is compared to the position of the hand provided by the high-accuracy OptiTrack motion capture system, together with the software development proposed in [15]. In a second step, this section analyzes whether the robotic arm is able to reach

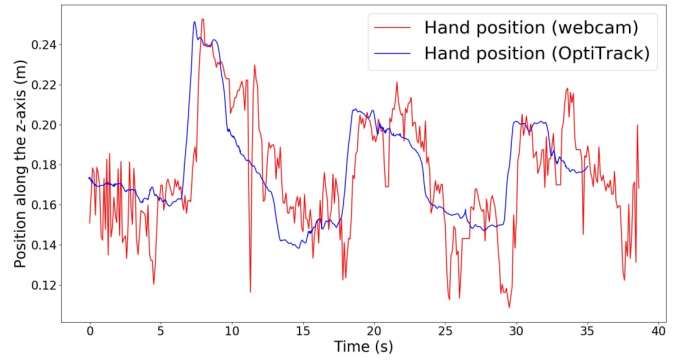


Fig. 3. Comparison between the true hand position (via the OptiTrack motion capture system) and hand position detected by the webcam along the  $z$ -axis

this position using the leader-follower approach described in Section III-A.

The human hand is not guided by any algorithm and its trajectory is entirely decided by the user. Therefore, the trajectories appears to be random, and unknown in advance, by the robotic arm system. To follow the hand position, and in order to assess the performance of the proposed image processing algorithm, a bracelet with reflective markers (that can be detected by the OptiTrack system) was designed. As it can be seen on Fig. 1.b, four grey passive reflective markers surround the bracelet. These reflective markers are detected by the 16 high-accuracy cameras of the OptiTrack motion capture system available in the flight arena of CentraleSupélec (see the cameras encircled in blue in Fig. 1.a), which then provide the bracelet position. The data given by the image processing algorithm described in Section IV-C are used to find the position of the purple colored marker (also glued on the bracelet) detected by the webcam.

There might be several sources of errors in the proposed image processing algorithm. Indeed, since only one webcam is used, occlusion or errors in the contour detection can hardly be handled. This leads to uncertainties during the detection of the purple marker position, or even the impossibility to detect it when the robot hides the marker. The position along the  $x$  and  $y$  axes is computed as the center of mass of the colored marker, which is more robust to errors than the detection of the edges of the marker. Thus, the results obtained with the algorithm match the real position of the colored marker, the error being of a few millimeters at most, which fulfills the requirements of this experiment. The position on the  $z$ -axis is computed by comparing the apparent size of the colored marker, i.e., its number of pixel, to its size at  $z = 0$ . Therefore, this method is easily affected by uncertainties in the detection of the contours of the marker, as it often happens because of the quality of the webcam or the robot occluding the marker. Therefore, although the average value matches the position of the human hand, the position returned by the algorithm fluctuates (see Fig. 3).

The errors sometimes add up to several centimeters on the  $z$ -axis, which is more than the ones encountered along

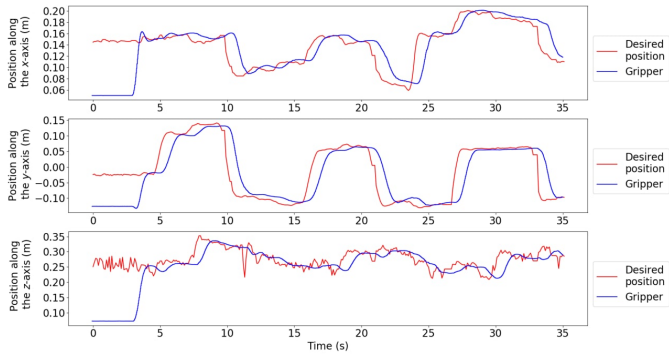


Fig. 4. Comparison of the  $x$ ,  $y$ , and  $z$  coordinates of the gripper with the position of the human's hand detected by the webcam

the  $x$  and  $y$  axes. However, since the leader-follower has a dynamics much slower than this identification algorithm, and since errors are random instead of systematic, the end-effector will move in average towards the position of the hand. The first experimental results are emphasized in a video available on [https://youtu.be/xCWzX\\_alrdg](https://youtu.be/xCWzX_alrdg). The delay that can be observed between the hand position (via the OptiTrack system) and the value returned by the webcam is due to the rate at which images are processed and sent to the robot to produce the reference signal.

The next step is to implement the leader-follower approach in the algorithm of the robotic arm to assess if this approach is effective to control the position of the end-effector of the robot. The desired position corresponding to the position of the colored marker (as calculated with the image processing algorithm) to which the *reference distance*, symbolizing the distance  $r_{i0}^*$  between the leader and the follower in the control law (see Section III-A), is subtracted and compared to the position of the end-effector. The results obtained with  $k_F = 10$  and a rate of 10 for the webcam and the robot (i.e., 10 actions per second) are depicted in Fig. 4.

Figure 4 shows that the end-effector of the robotic arm reaches the desired position returned by the webcam. This confirms that the leader-follower control law (3), using a single integrator dynamics, guarantees a zero static error:

$$\dot{\epsilon}_{i0}(t) = -k_F \cdot \epsilon_{i0}(t) \text{ thus } \epsilon_{i0}(t) \xrightarrow[t \rightarrow +\infty]{} 0. \quad (4)$$

However, the end-effector does not always exactly follow the marker. This is because its dynamics is slower than the human arm. Indeed, the robot needs some additional time to follow a change of the hand position. An analysis is provided in the next section.

### B. Tuning parameters analysis of the leader-follower control

We recall that the main goal of the proposed experimentation with human-robot interaction is to allow engineering students to learn the basis of Multi-Agent Systems control, for instance via a leader-follower approach. This section offers an analysis of the coefficient  $k_F$  used in the leader-follower control and the rate at which data is processed.

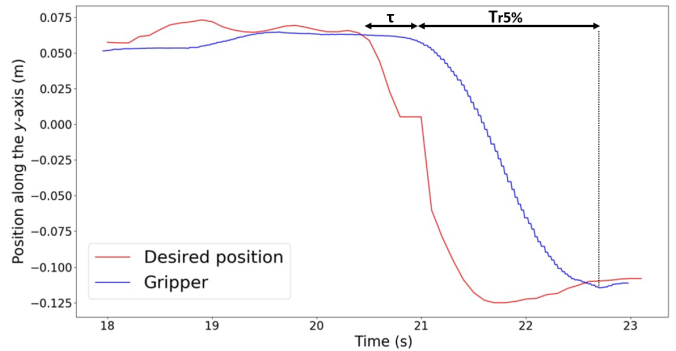


Fig. 5. Highlight of the delay  $\tau$  and the response time  $T_{r,5\%}$

TABLE I  
TUNING PARAMETERS

	Delay $\tau$ (s)	Time response $T_{r,5\%}$ (s)
$k_F = 5$ , rate = 10	0.6	2.4
$k_F = 8$ , rate = 10	0.6	2.0
$k_F = 10$ , rate = 10	0.6	1.8
$k_F = 10$ , rate = 20	0.5	1.8
$k_F = 15$ , rate = 20	0.5	1.5
$k_F = 20$ , rate = 20	0.5	1.3

Figure 4 illustrates a shift between the data from the webcam (desired position) and the actual position of the end-effector. This is due to two dynamical characteristics: the delay and the convergence speed. They reflect, respectively, the time needed for the robotic arm to react in response to a change of the hand position and the time needed to reach this position. The delay  $\tau$  is mostly due to the rate at which data are processed and transferred from the webcam to the robot, as well as to the inertia of the robotic arm. The absence of movement during the first few seconds are due to the time needed to initialize the robot, and are not considered as a delay. The convergence speed reflects the time needed by the robot to go from one position to another. In order to quantify it, the value  $T_{r,5\%}$ , corresponding to the time needed to cover 95% of the distance between its starting point and its goal, is assessed. These values are represented in Fig. 5.

Several experiments have been carried out for different values of the follower gain  $k_F$  and rate to assess how it impacts these dynamical characteristics (see Table I).

Table I highlights the impact of the parameters on the dynamics of the system. Indeed, it confirms that increasing  $k_F$  leads to a faster convergence, which matches the theoretical expectation (i.e.,  $\epsilon_{i0}(t) = \exp(-k_F t)$ ). Similarly, improving the rate slightly reduces the delay  $\tau$ . These values can therefore be modified to evaluate their impact in order to illustrate basic concepts on an introductory course to leader-follower control or to mobile robotics involving multi-robots with additional human-interaction.

Although it seems that increasing these parameters will improve the performance of the system, it is important to find the right balance. Indeed, the slow dynamics of the leader-

follower enables to mitigate the errors due to the identification algorithm performed on the webcam images, particularly important along the  $z$ -axis as it has been mentioned in Section V-A. It is also convenient to ensure that the robotic arm does not always remain over the marker in order to avoid occluding it from the camera. Increasing the dynamics of the system could also lead to collision with the human hand. Therefore, one has to be careful when increasing  $k_F$ . Similarly, increasing the rate would significantly increase the amount of data to handle, which might not be desirable.

## VI. OPENINGS FOR EDUCATIONAL EXPERIENCES

This laboratory experiment will be a starting point for future case studies proposed by our students during the teaching module on *Control of dynamical Multi-Agents Systems*. In order to facilitate the implementation of advanced control techniques on OpenMANIPULATOR-X, basic fill-in-the-gaps programs will be provided to the students, helping them to get starting easier.

Current work focuses on integrating the proposed robotic-arm experiment with the existing platform in the flight arena of CentraleSupélec. The goal is to provide students the possibility to implement advanced control on multi-agent systems, involving realistic multi-robot applications with human-in-the-loop. Therefore, in the near future students will be able to control at the same time a fleet of mobile-robots (ground vehicles such as TurtleBot Waffel with a robotic arm on top, together with TurtleBot Burger vehicles, and Crazyflie drones), with additional human-in-the-loop interactions. Developing control techniques for MAS with multiple robotic arms mounted on mobile-robots and human-in-the-loop is one challenge to be taken up. Another perspective is to develop fault-tolerant control algorithms to overcome situations when faults (e.g., sensor/actuator faults, communication delay/loss between the mobile robots and the robotic arms, etc.) could happen.

A long term perspective focuses on developing interactive games involving multi-robots and human interaction (e.g., playing ping-pong against a mobile robotic arm).

## VII. CONCLUSION

This paper proposed a new laboratory experiment to illustrate fundamental concepts on Control of Multi-Agent Systems involving human-robot interactions. It offers an easily reproducible robotic setup which requires a low-cost open-source robotic arm and a low-cost webcam. This experiment includes an intuitive human-robot interaction so that the students following this course are directly involved, thus improving their motivation and understanding of the concepts taught during this course (e.g., leader-follower-based control). The following repository [https://github.com/L2S-lab/Robotic\\_arm\\_ICSTCC2023](https://github.com/L2S-lab/Robotic_arm_ICSTCC2023) contains part of the code in order to help other institutes to replicate the proposed experiment and to help improving it. Future works will deal with an improvement of the tasks achievable by the robot. More advanced control methods, such as consensus-based control or model predictive control, could be implemented. Developing an impedance

control would also increase the human-robot interaction, thus improving the experience of the user, as well as serving as a demonstration for a Robotics course. Alternatively, this experiment can be also used for popularizing science activities (e.g., Open Day events). In this case, a human-like appearance could be given to the robot, as recent reports show that children tend to interact more with robots that have a behaviour similar to the human being (see [10]).

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