Adapted Laboratory for Mobile Robotics Teaching and its Application to Coordinated Control of Robots

David Gallarta Sáenz*, Pablo Álvarez Benito, Javier Rico-Azagra, Montserrat Gil-Martínez

Control Engineering Research Group, Department of Electrical Engineering, University of La Rioja, San José de Calasanz, 31, 26004 Logroño, Spain; **david.gallarta@unirioja.es*

SNE 32(2), 2022, 63-68, DOI: 10.11128/sne.32.tn.10602
Received: 2021-02-10 (selected EUROSIM 2019 Postconf. Publication; Revised: 2022-02-09; Accepted: 2022-02-15
SNE - Simulation Notes Europe, ARGESIM Publisher Vienna
ISSN Print 2305-9974, Online 2306-0271, www.sne-journal.org

Abstract. This paper presents a teaching laboratory especially suitable for practical work with mobile robotic systems. The laboratory is composed of a set of low-cost robots and a vision-based data capture system used to localise such robots with precision. All the generated information is centralised on a computer that acts as a link between the different elements. MATLAB-Simulink, a well-known programming environment, is used for information processing, and it also achieves maximum compatibility with the dynamic control tasks of the robots. To demonstrate the usefulness of the developed software and hardware infrastructure that comprise the laboratory, a coordinated control system involving several robots and using Lloyd's algorithm is presented.

Introduction

Nowadays, there is a growing interest in the use of robotic systems that replace, totally or partially, the intervention of human operators, which means that this type of technology has reached a high level of maturity. Traditionally, these solutions were focused on the use of fixed-base manipulators. However, in recent years there has been a fast growth of solutions based on the use of ground mobile robots, which introduce new challenges that future engineers must face.

The problems of estimation of attitude [1] and position [2, 3], the capture of information, the coordination of vehicles or the communication between fleets, represent technological challenges that will be essential for the professional development in the future.

Multi-robot systems [4-6] open a new field of study in mobile robotics, since they allow the optimization of multitude of applications and the development of new ones, helping to achieve objectives that are difficult to reach for a single robot. The control of multi-robot systems [7-9] is an area of science that has a great potential for development and that can involve important progress in mobile robotics in the coming years.

One of the main advantages of these systems is their versatility. A group of simple robots can carry out different types of more difficult tasks than a complex single robot could achieve. A multi-robot system presents great flexibility in terms of the number of robots that compose it and the different functions that each one can perform. This makes it possible to work in larger areas and allows to achieve the objectives in a more efficient way.

Another important attribute of these systems is redundancy: if a failure occurs in one of the agents, there is still a certain number of units that can continue carrying out the programmed tasks. There are mainly two types of coordinated control: formation control [10, 11] and coverage control [12]. In the first case, the goal is to make the robots position themselves in a certain way with respect to the others in order to accomplish a coordinated movement maintaining that formation. This allows the performance of different tasks at the same time. The second one consists in covering a certain area, distributing the space between several robots according to the requirements of each situation. This facilitates the possibility of covering large areas and reducing the necessary time to achieve the desired objectives.

In parallel with the arrival of these systems to our everyday life, the importance of teaching in this kind of technology has experienced a remarkable growth in recent years, increasing its relevance in the study programmes of the European Higher Education Area (EHEA).

As in other disciplines, laboratory practices are a fundamental element for acquiring the necessary competences. Nowadays, most of the practices about systems that use mobile robots in teaching are carried out through simulations, which does not imply a real contact for the student with situations that can be found beyond the classrooms. In addition, this type of tools generates a lower level of motivation in the student. The use of simulation tools instead of real systems is caused by the difficulty of having adapted and versatile laboratories, due to space limitations, economic issues or complexity in the implementation of solutions, which often exceeds the available time in a regular practice session.

In this paper, the development of a laboratory focused on the study of mobile robotic systems is described, together with its application to coordinated control of robots. The laboratory has the ideal requirements for the students to put their knowledge into practice in an environment that promotes learning through manipulation. It is a wide space, which has the necessary security conditions, as well as the functionalities of a 21st century technological context. This laboratory is designed to experiment and check the concepts used in robotic systems. Specifically, it can be used for practices focused on the modelling and control of aerial or ground robots, for the development of localisation and navigation systems, for the study of problems generated by odometry and for the coordinated control of flocks of mobile robots. Another advantage of this laboratory is that it can be built with a low budget and allows the possibility of working with MATLAB-Simulink, a familiar environment for the students, a fact that minimise their learning curve.

The paper is divided into four sections. The second one describes the laboratory, its elements and way of operation. The third section presents its application to coordinated control of mobile robots. Finally, the last one contains the conclusions.

1 Teaching Laboratory

The developed laboratory has mainly four elements: the working area, the vision-based data capture system [13], the used mobile robots and the software architecture that supports the system. These elements are described below.

1.1 Working Area and Vision-Based Data Capture System

The available working area has an approximate extension of 7 m × 7 m, enough space to carry out tests with ground robots and small multi-rotor UAVs (Unmanned Aerial Vehicle) [14]. On the edge of this enclosure there are eight Flex 3 cameras (see Fig. 1), commercialised by OptiTrack. These cameras are attached to a metal tube of 1 m long and 5 cm diameter, with a square base fixed to the ceiling by four screws. The support is complemented with a plastic clamp that has a ball joint on which the camera is held. This clamp allows the adjustment of the orientation and height along the tube.

The main application for which the eight Flex 3 cameras are installed is the tracking of ground robots [15] and drones [16]. The cameras are located according to the scheme shown in Figure 1. Its strategic placement tries to cover the largest possible area, since it must be taken into account that a point must be seen by at least three cameras. Once configured and calibrated, the system works with errors of estimation of position and orientation lower than 0.2 mm and 0.1º. Following this configuration, a capture area of 5 m × 5 m is available.

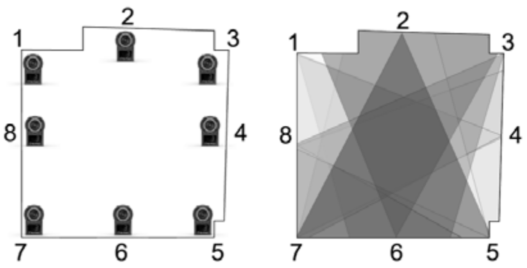

Figure 1: Layout of the cameras in the laboratory.

In order for the robots to be recognised by the cameras, they must have reflective markers, provided by Opti Track, randomly distributed over their structure. Figure 2 shows the placement of markers in a LEGO Mindstorms EV3 and its representation as a rigid body in Motive, Software provided by OptiTrack, used to process data captured by the cameras.

Finally, it can be noticed that a gray carpet has been placed on the floor of the working area (see Fig. 2), which has several functions, such as reducing the reflectance of the floor, preventing slipping of the wheels of mobile robots and buffering the impact in the case that a UAV crashes into the floor.

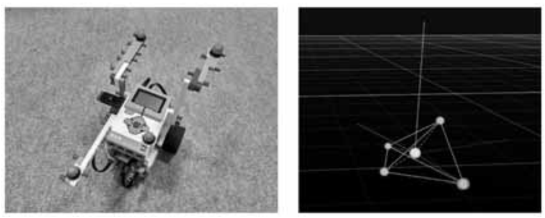

Figure 2: Markers in a LEGO EV3 robot and its representation in Motive.

1.2 Mobile Robots

In the laboratory, it can be used any type of mobile robot capable of communicating with Simulink. Mainly, multi-rotor UAVs are used, in which the installed flight controller belongs to the APM family [17], and ground mobile robots based on the LEGO Mindstorms EV3 platform [18, 19]. In this paper, the described application is for this last robot.

The LEGO Mindstorms EV3 is a kit focused on education, traditionally used in secondary education courses to get a first glimpse of robotics [20, 21]. However, the existence of a Simulink library of specific blocks for this family of robots, makes it possible to experiment with techniques used in industrial robots [22], so this robot is an exceptional work tool for students at university level. In addition, its low cost makes it accessible to schools and universities, where sometimes the available budget does not allow to obtain other types of useful robots for teaching due to their high price. An important feature of this robot is that, since it is assembled from scratch with different pieces, it permits to get different configurations according to the desired use. Thanks to the multiple included accessories (colour sensor, touch sensor, ultrasonic sensor...), it is possible to get to know techniques used on a larger scale in the industry. This versatility also means that there are not many difficulties when it comes to repairing the robot, since it is enough to replace the damaged part. This, added to the facility to find spare parts, makes maintenance easy.

Despite the advantages mentioned above, the LEGO Mindstorms EV3 platform is not defect-free. Its main problems are the low power of its motors and the low precision of the built-in sensors, which give rise to important errors when estimating the state of the vehicle using only odometry-based techniques. In this case, the use of the vision-based data capture system solves this problem.

1.3 Software Architecture and Communication System

The communication system used to send and receive information between the different elements that compose the system is shown in Figure 3. In this figure, it can be verified that all the elements are in a type C VLAN (Virtual Local Area Network) generated with a router. It connects the LEGO EV3 robots and the PC on which the tests are executed through Wi-Fi, It can be used an Ethernet link for the PC if desired.

It is recommended to connect only the elements used in the laboratory to the mentioned network, in order to reduce the data traffic and avoid packet losses. Note that the transmission of packets between the PC and the EV3 robots is carried out using the UDP protocol. As for the coding of the network, it can be open or it can be used a WPA encryption, the only one supported by the brick EV3.

As illustrated in Figure 3, the information from the cameras is received by the PC using two OptiHub hubs, each one of which includes four cameras connected via USB. At the same time, the hubs are connected to each other and to the PC for the synchronization of the captured data. The Motive software automatically manages the information and estimates the position of the bodies. The data generated by Motive is internally broadcasted using the VLAN. It can be noticed how the generated information is centralised in real time on the PC. In this way, the PC acts as a sender and as a receiver, transmitting the necessary information to each element of the system.

Regarding the programming of the different devices, there are multiple alternatives, depending on whether the system works with a single robot or with several robots and if a centralised or distributed architecture is desired. In the most general case, that uses several mobile robots, *n+1* Simulink models must be developed, one for each of the n robots that work in the application and one last model that coordinates the information, which is executed on the PC.

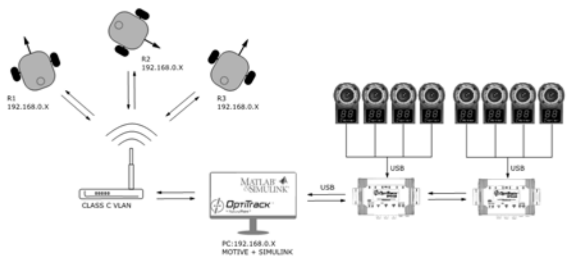

Figure 3: Communication between the different elements in the laboratory.

As previously mentioned, the Simulink model that is executed in each one of the robots exchanges data with the PC using the UDP protocol. For example, the positioning references can be sent from the PC to the robots as coordinates, indicating the point to which they should move, and the robots can send the data generated by their sensors to the PC to close the control loop. The Simulink model executed on the PC can also receive the data collected by Motive, which can be used in monitoring tasks or in the development of control strategies.

2 Application of the Laboratory to Coverage Control

In this section, a solution to the problem of coverage with three LEGO Mindstorms EV3 robots is presented. The main objective is to illustrate how the laboratory works, its possibilities and the results obtained.

2.1 Differential Drive Robot and its Control as an Elemental Unit

In this case, the EV3 robots are configured to work as differential drive robots, which means using two wheels located on a common axis and each one coupled to its own motor and controlled independently. This kind of robot is the most used in laboratories because of the simplicity of its design and its manoeuvrability. Despite its simplicity, this configuration allows to develop numerous tasks, which makes this robot a great tool for student learning.

In order to perform the control of the differential drive robot, it is necessary to implement a hierarchical control structure with several levels. In the lowest level, the speed control of each one of the wheels is placed. For this control, the student must carry out the experimental identification of the motor and close the feedback loop designing the appropriate controller. In a second hierarchical level, the control loop responsible for the movement of the robot is located. The aim of this control loop is to adjust the linear and angular speed applied to the robot so that it reaches the desired position. To achieve this, two control loops are combined: one of them includes the speed controller for the longitudinal dynamics and the other one contains the direction controller for the lateral dynamics. To close these control loops, odometry-based techniques or the information generated by the cameras of the OptiTrack system can be used. Figure 4 shows the Simulink diagram used in the proposed application, which runs on the three used robots.

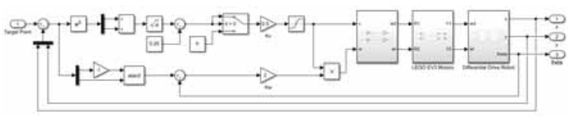

Figure 4: Simulink model implemented in the EV3 robots.

2.2 Coverage Control Algorithm

The implemented coverage control attempts to achieve that the three robots used in the experiment cover a certain area in an efficient manner. To that end, this area is divided into as many parts as robots are used, and the resultant regions are meant to have a similar size.

The used technique is based on Lloyd's algorithm [9], an iterative algorithm that seeks to find a centroidal Voronoi tessellation [23] for a set of points within a certain area. A centroidal Voronoi tessellation is a special type of Voronoi diagram in which the point that generates each one of the cells matches its centroid, obtaining a uniform distribution of the cells. During each iteration, Lloyd's algorithm generates the Voronoi diagram of the given set of points, calculates the centroid of each one of the resulting cells and moves each point towards the centroid of its corresponding cell to generate a new Voronoi diagram. The algorithm is repeated until reaching a centroidal Voronoi tessellation.

This algorithm presents an important feature that makes its implementation very simple: there is no possibility of collisions between robots. The reason for this situation is that the reference point that each robot has to reach is always within its own cell, so that the trajectories of the robots do not bump into each other at any time.

The presented algorithm is implemented in Simulink, taking as input points the positions of each robot. The output points are the coordinates to which each robot must move.

2.3 Results

The obtained results are illustrated below. The initial and final positions of the robots are shown in Figure 5, both in reality and in the reconstruction created by Motive.

In the first experiment, the internal control loop of each one of the robots is closed using the information generated by their encoders. This experiment is carried out in order to illustrate the problems related to the encoders, since they are not a reliable positioning system, in contrast to the vision-based data capture system available in the laboratory.

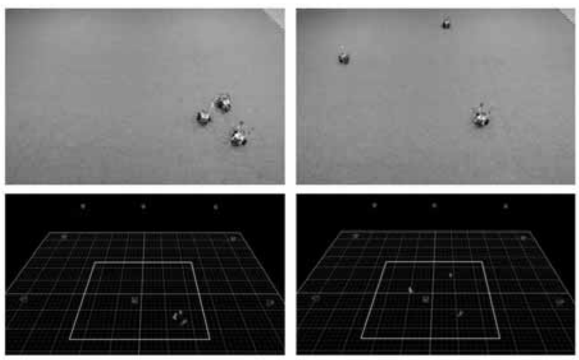

Figure 5: Initial (left) and final (right) position of the robots.

As it is shown in Figure 6, each one of the robots has moved in search of its consecutive reference points (black colour), assigned by the coverage control algorithm. If a thorough analysis is not carried out, it may seem that the robots have achieved their objective. However, the distortion produced by an erroneous estimation of the position of the robots due to the low accuracy of their encoders, which is evident in the curves (see Figure 6 down), leads to an inappropriate coverage.

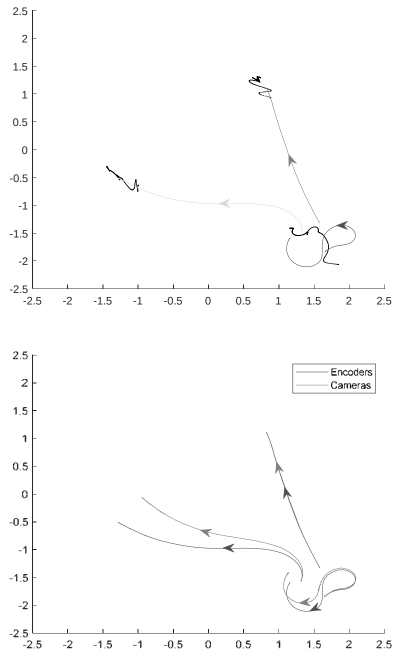

Figure 6: Described trajectory by each robot until reaching its final position (up). Comparison between the trajectories estimated by the encoders and the real trajectories captured by the cameras (down).

As it can be seen in Figure 7 (right), the cells assigned to each robot have different sizes. The best example is the cell occupied by the robot in the lower right corner (blue colour), that is significantly smaller than the rest.

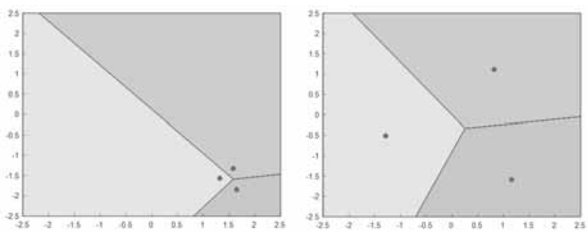

Figure 7: Initial and final distribution of the cells for each robot.

In the second experiment, the test described above is repeated, but in this case, using as feedback the current positions obtained with the vision-based data capture system. At the end of the test, a greater uniformity in the size of the cells can be appreciated (see Figure 8), since the coverage algorithm works more accurately. This experiment shows the importance of using a system that allows to determine with precision the position of the mobile robots. This problem would be more serious if the accumulation of errors in the estimation of the position of the robots involves collisions between them.

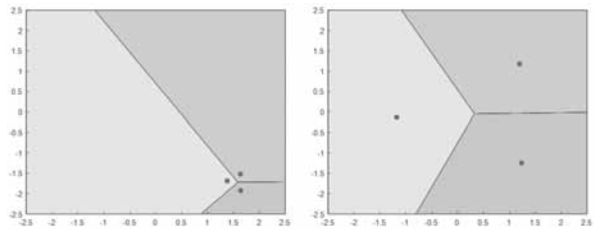

Figure 8: Initial and final distribution of the cells for each robot when the information captured by the cameras is used for the feedback.

Although the areas of the cells in the final situation of this second experiment are more compensated than in the first one, the space is not perfectly distributed. This is because the robots maintain a safety distance of 25 cm to the target point to ensure a better behaviour, so they never reach that point. This situation exists in both the first and the second experiment. It can be observed in Fig. 6 (left) that none of the robots finishes its trajectory at the end of the black line (reference points). In the case of the robot located on the left, that distance would reduce the size of its cell to the benefit of the other two. As the working area is only 5 m × 5 m, the difference between the final size of the cells is quite noticeable. However, considering that this type of systems is usually used in large areas, this difference would be insignificant.

3 Conclusions

It has been presented a laboratory that may be of interest for teaching systems that use mobile robotics. Its main advantages are its simplicity, low cost and reduced learning curve. Having all the information generated by the system in a single software (MATLAB-Simulink) brings numerous benefits for the student, who does not have to face a new development environment.

The proposed application example shows the advantages of the teaching laboratory.

In the implemented application, a coverage control is carried out with three differential drive robots built with the LEGO Mindstorms EV3 platform. This experiment evidences the problems generated when the control loops of the robots are closed using techniques based on odometry. In addition, it is illustrated how these problems can be solved using the vision-based data capture system built in the laboratory.

Acknowledgements

The authors are grateful for the assistance provided by the Government of La Rioja through the I+D ADER 2017-I-IDD-00035 project and by the University of La Rioja through the Help to Research Groups REGI 2018/42.

References

[1] Rico-Azagra J, Gil-Martínez M, Rico-Azagra R, Maisterra P. Low-cost attitude estimation for a ground vehicle. Robot 2015: Second Iberian Robotics Conference, Advances in Intelligent Systems and Computing, 121-132 (2016).

[2] Gonzalez J, Stentz,A, Ollero A: A Mobile Robot Iconic Position Estimator using a Radial Laser Scanner. Intelligent & Robotic Systems 13, 161-179 (1995).

[3] González J, Ollero A. Estimación de la Posición de un Robot Móvil. Informática y automática: revista de la Asociación Española de Informática y Automática 29(4), 3-18 (1996).

[4] Badran M, Khan R, Fauziah S, Zainal Z. Collaboration in multi-robot systems. ARPN Journal of Engineering and Applied Sciences 10(22), 17225-17231 (2015).

[5] Parker L.E. Current Research in Multi-Robot Systems. Journal of Artificial Life and Robotics 7(1-2), 1-5(2003).

[6] Gautam A, Mohan S. A Review of Research in Multi-Robot Systems. IEEE 7th International Conference on Industrial and Information Systems, (2012).

[7] Yan Z, Jouandeau N, Ali Cherif A. A Survey and Analysis of Multi-Robot Coordination. International Journal of Advanced Robotic Systems 10(399), 1-18, (2013).

[8] Bullo F, Cortés J, Martínez S. Chapter 5: Deployment. In: Princeton University Press, Princeton and Oxford. Distributed Control of Robotic Networks, A Mathematical Approach to Motion Coordination Algorithms, pp. 214–242 (2009).

[9] Cortés J, Egerstedt M. Coordinated Control of Multi-Robot Systems: A Survey. SICE Journal of Control, Measurement, and System Integration 10(6), 495–503 (2017).

[10] Mastellone S, Stipanović D, Spong M. Remote Fomation Control and Collision Avoidance for Multi-Agent Nonholonomic Systems. Proc. of the IEEE International Conference on Robotics and Automation, pp. 1062-1067. Roma, Italy, April 2007.

[11] Balch T, Arkin R. Behavior-based Formation Control for Multi-robot Teams. IEE Transactions on robotics and automation 14(8), (2001).

[12] Ranjbar-Sahraei B, Weiss G, Nakisaei A. A Multi-Robot Coverage Approach based on Stigmergic Communication. German Conference on Multiagent System Technologies 7598, 126-138 (2012).

[13] Atiya S, Hager G. D.: Real-Time Vision-Based Robot Localization. IEEE Transactions on Robotics and Automation 9(6), (1993).

[14] Gallarta D, Rico-Azagra J, Nájera S, Gil-Martínez M. Laboratorio para el desarrollo de sistemas de navegación y control para UAVs multirotor. Proceedings of the XXXIX Jornadas de Automática, pp. 613-620. Badajoz, Spain, September 2018.

[15] Vincze M, Prenninger JP, Gander H. A Laser Tracking System to Measure Position and Orientation of Robot End Effectors Under Motion. The International Journal of Robotics Research 13(4), 305-314 (1994).

[16] Mueller M, Smith N, Ghanem B. A Benchmark and Simulator for UAV Tracking. Proceedings of the 14th European Conference on Computer Vision, pp. 445-461. Amsterdam, The Netherlands, October 2016.

[17] MathWorks Website, www.mathworks.com/matlabcentral/fileexchange/39037-apm2-simulink-blockset, last accessed 2019/06/11.

[18] Korkmaz Ö. The Effect of Scratch- and Lego Mindstorms Ev3-Based Programming Activities on Academic Achievement, Problem-Solving Skills and Logical-Mathematical Thinking Skills of Students. Malaysian Online Journal of Educational Sciences 4(3), 73-88 (2016).

[19] Danahy E, Wang E, Brockman J, Carberry A, Shapiro A, Rogers C. LEGO-based Robotics in Higher Education: 15 Years of Student Creativity. International Journal of Advanced Robotic Systems 11(27), (2014).

[20] Cerezo F, Sastrón F. Laboratorios Virtuales y Docencia de la Automática en la Formación Tecnológica de Base de Alumnos Preuniversitarios. Revista Iberoamericana de Automática e Informática industrial 12, 419–431 (2015).

[21] Ospennikova E, Ershov M, Iljin I. Educational Robotics as an Innovative Educational Technology. Procedia - Social and Behavioral Sciences 214, 18–26 (2015).

[22] Koc AB, Liu B. Demonstrating Tractor Rollover Stability Using Lego Mindstorms and Smartphones. Journal of Agricultural Systems, Technology, and Management 24, 1-11 (2013).

[23] Du Q, Faber V, Gunzburger M. Centroidal Voronoi Tessellations: Applications and Algorithms. SIAM Review 41(4), 637-676 (1999).