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Carrera de Ingeniería en Electrónica e Instrumentación

Artículo académico, previo a la obtención del título de Ingeniero en Electrónica e Instrumentación.

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Enero, 2022

Unicycle Mobile Robot Formation Control in *Hardware in the Loop* Environments

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Abstract. This work presents the development of a formation control algorithm for three unicycle-type robots, to solve the problem in the implementation of controllers oriented to collaborative functions and also subject to an excessive economic cost. This leads to the approximation of the simulation technique in environments Hardware in the loop (HIL), which allow clearly visualize with a real idea and a high percentage of approximation of the behavior of mobile robots unicycle type integrating different types of advanced controllers that will allow the execution of tasks of mobile robots unicycle type the same that are determined by the trajectories that control the position and thus raises the strategy of nonlinear control with a centralized and decentralized formation in the work area, acting as a command and control management system that will in turn be able to receive input signals, process the information and deliver control signals, which will later be displayed and analyzed to help verify the control theory.

Keywords: Formation control · Unicycle type robot · Mathematical modeling · Control theory and analysis

1 Introduction

Industrial robots have been considered the most popular robots; due to the importance they have maintained in the industrial sector as a key tool in modernizing [1]. However, in recent years the need has arisen to extend the scope of application of robotics outside the area of the purely industrial sector, thus trying to make the robots perform tasks like the demanded in service robotics [1, 2]. Thus, its use has evolved both in its characteristics and in its maneuverability in the execution of high-impact actions within society. Several definitions they have been imparted around a robot of service, it is so that the International Federation of Robotics (IFR, for their initials in English), organism that is in charge to coordinate the activities in this technological area it has defined it as: A robot that operates of automatic way or semiautomatic to carry out useful services to the well-being of the humans or to their equipment, excluding the operations of manufacture. The name arises for the restlessness of the scientific community of carrying out developments destined to be to the service of the society, trying that this one recognizes and endorses their results [3].

M. Botto-Tobar et al. (Eds.): ICAT 2020, CCIS 1388, pp. 1–14, 2021.
https://doi.org/10.1007/978-3-030-71503-8_33

It is evident and certain at the same time that the robots, are the systems that in a future will perform most of the tasks oriented to the physical highlighting the heaviest, in this section is detailed the sectors as possible main users of these robots are: Agriculture, construction, mining, energy, space, security and defense. In all of them, and in many others [4], In the field of robotics, there are a large number of tasks that must and can be robotized, which requires the development of specific robots, a task that manufacturers are not able to perform but only research centers. As for the physical structure, there are more and more demands regarding the characteristics of these. One can speak of robots with extremely large and small dimensions capable of entering dangerous, inaccessible and complex places for humans, thus contributing to the development of various activities that benefit society. The great variety of environments and situations in which they can develop requires locomotion capabilities developed according to their purpose may be these based on wheels or legs, [5]. Among the most relevant contributions in the field of locomotion have been automatic car driving systems, underwater robots, climbing and airborne robots, as they require hostile environments as well as air and water, thus becoming a center of attraction for researchers specializing in mobile robots.

Mobile robotics is an active research area where every day the world finds new technologies to improve the intelligence of mobile robots and their respective areas of application, these robots are characterized by the ability to: roll, slide, walk, jump, etc., [6]. Among the different mobile robots, there are the following types of robots: unicycle, car-like and omnidirectional. The unicycle type mobile robots are the most used due to its good mobility and simple configuration, these robots are specialized in sectors such as: floor cleaning, surveillance and industrial charge transport using autonomous guided vehicles [6, 7], These robots consist of a structure with 3 or 4 wheels, which in turn consist of a series of rollers that allow the wheel to move flexibly in two directions (together with the wheel and together with the roller) in the coordinate frame [8] The Car-like mobile robot is composed of an electric system, *i.e.,* a motor with drive on the rear wheel and steering on the front wheel [9].

In recent years, the formation and coordination of multiple robots has been an area of intense research. Various applications in the field of robotics and automatic control allowed a great boom in the scientific community. One of the existing alternatives is the control in formation based on different methods that are classified within three conventional ones: leader follower or master/slave [10, 11], based on behavior, [12], and virtual structures. Many of the multi-vehicle coordination algorithms, such as [8], it considers only robots of punctual mass with dynamics of simple or double integrator, where the robot can be moved instantaneously in any direction on the plane. The robots uniciclo with different characteristics, require the synchronization of their movements to achieve to maintain the formation and this way to follow a predefined path [13]. In the presence of disturbances, robots must work cooperatively to recover their trajectory and formation. In addition, the robots can go in and out of the formations, so the rest of the formation must be adjusted to the maximum speed conditions that will be reached by all the members of the group. The problem of formation multiple robots has been studied through different approaches including the implementation of controllers.

Therefore, the proposal of this article is the implementation of a formation control algorithm through Hardware in the loop, in this work the formed robotic assembly moves along a path with a desired speed, simultaneously it can alter the formation of the whole assembly through the modification of the distances and orientations of the main and secondary projections. The proposed controller uses a hierarchical control structure, in order to provide scalability to the system and at the same time not saturate the processing unit, thus merging the centralized and decentralized information processors. In a high level hierarchy, a centralized computer is in charge of generating the control actions to achieve the secondary projections, while, at a local level, each member of the heterogeneous robotic assembly includes its own processing unit to achieve kinematic and dynamic control and also to provide feedback [14], which is shared through wireless communications by means of Raspberry Pi cards.

This article is divided into six sections, including the introduction. Section 2 presents the system structure, the description of the HIL and its VR environment, while Sect. 3 presents the kinematic and dynamic modeling of the unicycle robot. Section 4 presents the scheme, design and stability analysis of the formation control algorithm for three or more robots. Section 5 presents the experimental results obtained with the implementation of the HIL and finally the conclusions of this work are presented in Sect. 6.

2 System Structure

The Hardware in the Loop (HIL) environment, which is a simulation technique used for the visualization, development and testing of the behavior of complex embedded systems in real time, aims to implement an HIL environment in order to develop advanced control algorithms for the formation of three mobile robots of the unicycle type. The HIL to be implemented will consider so much the kinematic part as the dynamics of the mobile robot of type unicicle.

The system proposed in this work (to see Fig. 1) it consists of a controller advanced of centralized formation, based on a system of management of command and control, where it is considered as entrance the task desired (position) for the three robots mobile of type unicicle, where each robot follower will send signals to the robot leader the same that will process the information and it will resend signals of execution for the task assigned. In addition, with the purpose to emulate a real robot in the structure HIL it will be implemented controllers PID for each actuator of the mobile robots, that is to say, two PID that will compensate the dynamics of the mobile robot. Later, it will be developed an intuitive graphical interface that allows the user interaction with each mobile robot, in order to evaluate the behavior of the robotic system and the evolution of control errors. The HIL will be developed in a master control unit that allows bilateral wireless communication with the advanced controller and independent structures of each of the mobile robots, in order to close the control loop.

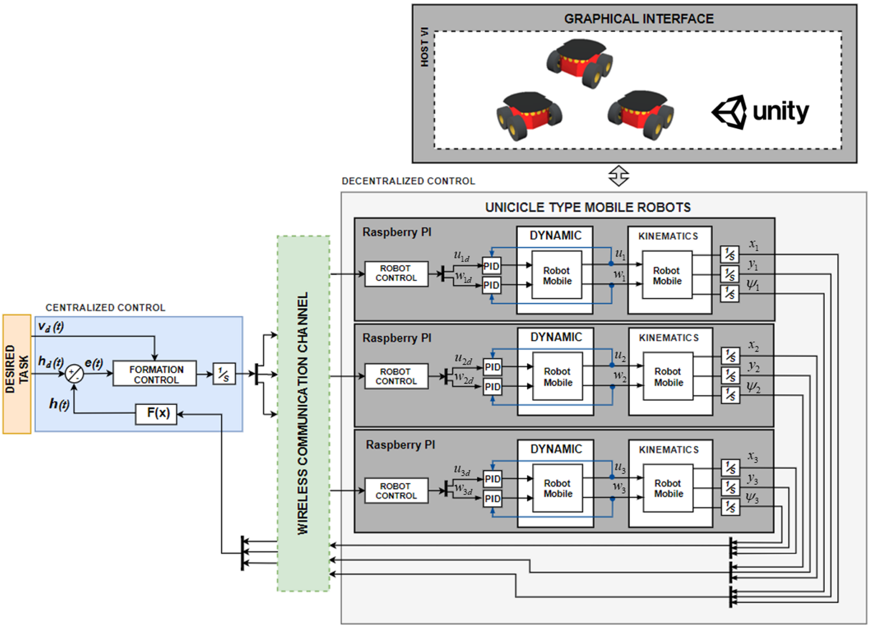


Fig. 1. Diagram of the proposed system.

3 Mobile Unicycle Robot

In the field of applied robotics both kinematic and dynamic models are widely used for the design of different control algorithms, as needed. Next, it is presented the kinematic and dynamic model of unicycle robots considering the restrictions of movement that it has.

3.1 Kinematic Model

When a mobile robot performs desired tasks or actions at low speeds and with a small load or weight in relation to its structure, the best option for controller design is the kinematic model. Figure 2 defines the geometry of the mobile robot type unicycle.

Where G represents the center of mass of the mobile robot which is at a distance a forward of the axis of the moving reference system $\{R_m\}$, considering that x and y belong to the position of the point $\mathbf{h}$ with regard to the global reference system; and finally ψ defines the orientation of the mobile robot with respect to $\{R\}$.

It is of vital importance to consider the restrictions of movement that the mobile robot presents, in this case it is considered the non-holonomic restriction which determines that the mobile robot can only be moved perpendicularly to the axis that joins the motors, and it is given by:

$$\dot{x}\sin(\psi) + \dot{y}\cos(\psi) + a\psi = 0 \qquad (1)$$

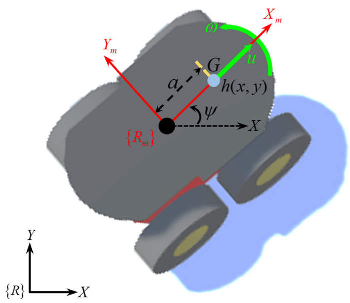


Fig. 2. Model of the kinematic structure of the robot

considering this restriction, the kinematic model of the mobile robot, can be represented by:

$$\begin{cases} \dot{x} = u\cos(\psi) - a\omega\sin(\psi) \\ \dot{y} = u\sin(\psi) + a\omega\cos(\psi) \\ \dot{\psi} = \omega \end{cases} \tag{2}$$

the system of Eqs. (2) can be written in a compact form as:

$$\begin{aligned} \dot{\mathbf{h}}(t) &= \mathbf{J}(\psi)\mathbf{v}(t) \\ \dot{\psi}(t) &= \omega(t) \end{aligned} \tag{3}$$

where $\dot{\mathbf{h}} = \begin{bmatrix} \dot{x} \; \dot{y} \end{bmatrix} \in \Re^2$ represent the velocity vector of the axis; $\mathbf{J}(\psi) = \begin{bmatrix} \cos\psi & -a\sin\psi \\ \sin\psi & a\cos\psi \end{bmatrix} \in \Re^{2x2}$ is a unique matrix; and defines the maneuverability control of the mobile robot $\mathbf{v} \in \Re^n$ and $\mathbf{v} = \begin{bmatrix} u \; \omega \end{bmatrix}^T \in \Re^2$ in which u and ω represent the linear and angular speeds of the mobile robot, respectively.

3.2 Dynamic Model

Generally, the existing robots on the market have a low level in terms of reference speeds of PID controllers to monitor input speeds and which do not allow the motor voltage is directly proportional. Therefore, it is useful to express the dynamic model of the mobile robot unicycle type conveniently considering the linear and angular speed as input signals, all in order to use this model in controller design. Then, the model of the mobile robot can be expressed as [15, 16]

$$\mathbf{v_{ref}} = \mathbf{M}(\varsigma)\dot{\mathbf{v}} + \mathbf{C}(\varsigma, \mathbf{v})\mathbf{v} \tag{4}$$

where, $\mathbf{M}(\varsigma) \in \Re^{nxn}$ with $n = 2$ and $\mathbf{M}(\varsigma) = \begin{bmatrix} \varsigma_1 & -\varsigma_7 \\ -\varsigma_8 & \varsigma_2 \end{bmatrix}$ represents the inertia of the robot-mobile system; $\mathbf{C}(\varsigma, \mathbf{v}) \in \Re^{nxn}$ and $\mathbf{C}(\varsigma, \mathbf{v}) = \begin{bmatrix} \varsigma_4 & -\varsigma_3\omega \\ \varsigma_5\omega & \varsigma_6 \end{bmatrix}$ represents the components of the centripetal forces; $\mathbf{v} \in \Re^n$ and $\mathbf{v} = [u\ \omega]^T$ is the speed vector of the system; $\mathbf{v}_{ref} \in \Re^n$ and $\mathbf{v_{ref}} = \left[u_{ref}\ \omega_{ref} \right]^T$ is the vector of speed control signals for the mobile robot; and $\varsigma \in \Re^l$ with $l = 8$ and $\varsigma = \left[\varsigma_1\ \varsigma_2 \ldots \varsigma_l \right]^T$ is the vector that contains the dynamic parameters of the mobile robotic system.

4 Multilayer Scheme

In this section is presented the distribution of variables that make up the cooperative control of mobile robots, which is composed of three main layers, *i.e.,* centralized, decentralized and virtual environment, see Fig. 3. The main layers are divided into six secondary layers where two of them correspond to the main layer of the centralized and the remaining four correspond to the decentralized layer. The six secondary layers are described as follows: *i) Task Planning* This layer establishes the characteristics of the environment where the desired formation task is planned to be executed either online or offline based on the configuration of the initial parameters: desired path, initial positions of the mobile robots and formation structure. *ii) Formation control* has the purpose of calculating the different control actions so that the mobile robots maintain a position so that the desired formation is satisfied. *iii) Environment* represents the communication channel which allows a closed-loop control between the centralized control and the independent structure of each of the mobile robots. *iv) Non-Linear*

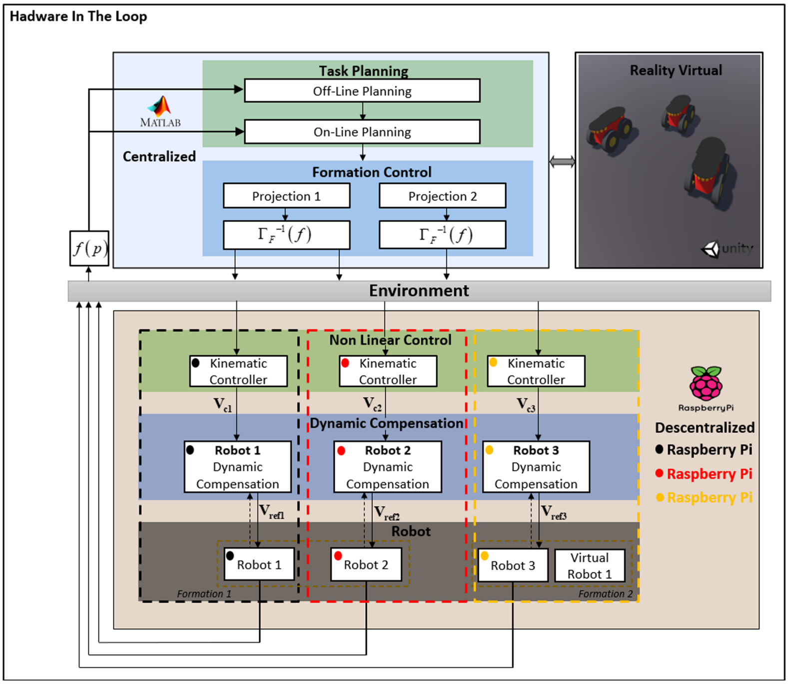


Fig. 3. Multilayer control scheme.

Control is responsible for providing maneuverability speeds to each robot that make up the system, taking as reference the control actions generated by the formation control. *v) Dynamic Compensation* Its main objective is to compensate the dynamics of each of the mobile robots, thus reducing the speed tracking error and limiting it near zero. *vi) Robots* represents the set of mobile robots considered for the formation system.

5 Control Schemes

The proposed control scheme to fulfill collaborative and trajectory tracking tasks is shown in Fig. 4, the controller design is mainly based on two main blocks. A centralized control block itself that is responsible for managing all data from the mobile robots for them to apply the control of formation of the 3 mobile robots, and on the other hand a decentralized control block which is confirmed by 3 control algorithms each for each robot, this means that each of the robots can have different dynamic characteristics.

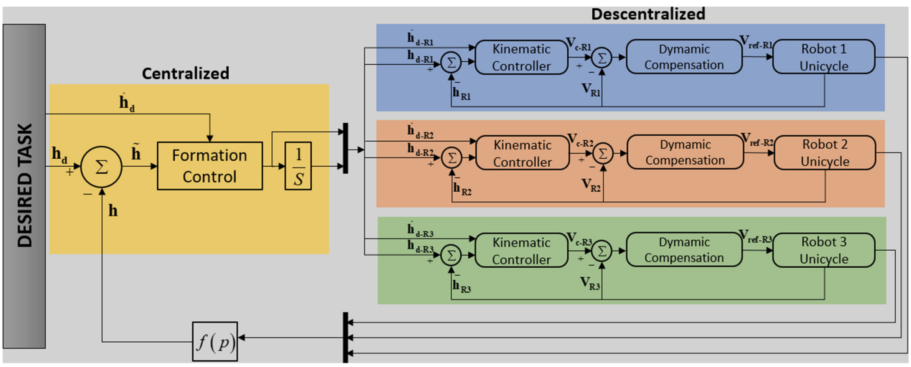


Fig. 4. Control structure for formation

5.1 Formation Control

The design of the proposed formation controller is developed based on projections given between a pair of mobile robots. Under these considerations to be able to meet the formation tasks required between three mobile robots is necessary to add a virtual robot, Fig. 5 defines the geometry of the formation task to be analyzed.

Direct kinematic transformations $f(.)$ For both projections they are given by:

$$\gamma_V = \begin{bmatrix} \mathbf{p_V} \\ \mathbf{s_V} \end{bmatrix}; \mathbf{p_V} = \begin{bmatrix} x_V \\ y_V \end{bmatrix} = \begin{bmatrix} \frac{1}{2}(x_1 + x_2) \\ \frac{1}{2}(y_1 + y_2) \end{bmatrix}; \mathbf{s_V} = \begin{bmatrix} d_V \\ \theta_V \end{bmatrix} = \begin{bmatrix} \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \\ \tan^{-1}\left(\frac{y_1 - y_2}{x_1 - x_2}\right) \end{bmatrix},$$

$$\gamma_O = \begin{bmatrix} \mathbf{p_O} \\ \mathbf{s_O} \end{bmatrix}; \mathbf{p_O} = \begin{bmatrix} x_O \\ y_O \end{bmatrix} = \begin{bmatrix} \frac{1}{2}(x_V + x_3) \\ \frac{1}{2}(y_V + y_3) \end{bmatrix}; \mathbf{s_O} = \begin{bmatrix} d_O \\ \theta_O \end{bmatrix} = \begin{bmatrix} \sqrt{(x_V - x_3)^2 + (y_V - y_3)^2} \\ \tan^{-1}\left(\frac{y_V - y_3}{x_V - x_3}\right) \end{bmatrix},$$

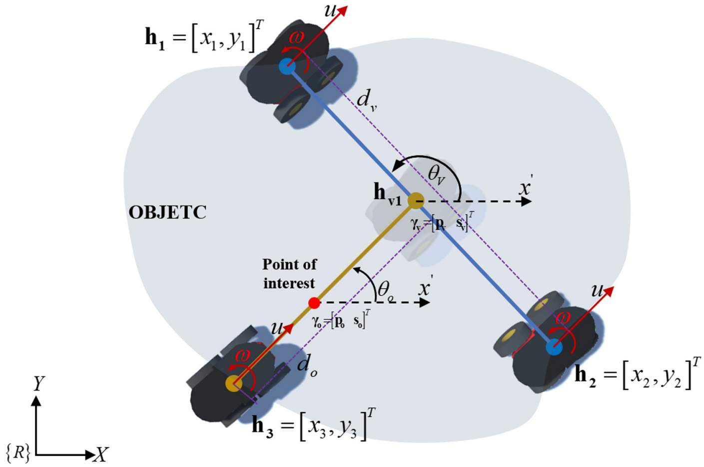


Fig. 5. Analysis of the formation of unicycle robots.

taking the time derivative of the forward and backward kinematic transformations so that the relationship between the time variations of $\dot{\mathbf{h}}(\mathbf{t})$ and $\dot{\boldsymbol{\gamma}}(\mathbf{t})$, represented by the Jacobian matrix $\mathbf{J_F}$, that is given by:

$$\dot{\boldsymbol{\gamma}} = \mathbf{J_F}(\mathbf{h})\dot{\mathbf{h}} \tag{5}$$

That is why the desired position and shape parameters are considered when designing the formation controller $\boldsymbol{\gamma_d} = \left[\,\mathbf{p_d}\ \mathbf{s_d}\,\right]$ and desired speed variations $\dot{\boldsymbol{\gamma}}_\mathbf{d} = \left[\,\dot{\mathbf{p}}_\mathbf{d}\ \dot{\mathbf{s}}_\mathbf{d}\,\right]$. Therefore, the formation error can be defined as $\tilde{\boldsymbol{\gamma}} = \boldsymbol{\gamma_d} - \boldsymbol{\gamma}$ obtaining the time derivative denoted as $\dot{\tilde{\boldsymbol{\gamma}}} = \dot{\boldsymbol{\gamma}}_\mathbf{d} - \dot{\boldsymbol{\gamma}}$. However, defining the control objective as $\tilde{\boldsymbol{\gamma}}(\mathbf{t}) = \mathbf{0}$ this to demonstrate the stability of the system. To achieve this is proposed a driver based on a Lyapunov candidate function which is defined as $\mathbf{V}(\tilde{\boldsymbol{\gamma}}) = \frac{1}{2}\tilde{\boldsymbol{\gamma}}^\mathbf{T}\boldsymbol{\gamma} > 0$, Considering the temporal derivative of this function, is obtained $\dot{\mathbf{V}}(\tilde{\boldsymbol{\gamma}}) = \tilde{\boldsymbol{\gamma}}^\mathbf{T}\boldsymbol{\gamma}$.

Now, the proposed formation control law is defined as:

$$\dot{\mathbf{h}}(\mathbf{t}) = J_\mathbf{F}^{-\mathbf{1}}\left(\dot{\boldsymbol{\gamma}}_\mathbf{d} + \mathbf{K}\mathbf{tanh}(\tilde{\boldsymbol{\gamma}})\right) \tag{6}$$

where $\mathbf{K}$ is a diagonal gain matrix. Replacing (6) in the temporal derivative of $\dot{\mathbf{V}}(\tilde{\boldsymbol{\gamma}})$, is obtained

$$\dot{\mathbf{V}}(\tilde{\boldsymbol{\gamma}}) = -\,\tilde{\boldsymbol{\gamma}}^\mathbf{T}\mathbf{K}\mathbf{tanh}(\tilde{\boldsymbol{\gamma}}) < 0 \tag{7}$$

So the law of closed-loop control (6) is asymptotically stable, *i.e.,* that formation control errors $\tilde{\boldsymbol{\gamma}}(\mathbf{t}) \to 0$, is asymptotically stable with $t \to \infty$.

5.2 Kinematic Control of the I-th Robot

The purpose of implementing a control algorithm is to find the maneuverability vector to achieve the desired operational movement of the robot. Thus, the proposed control algorithm is based on the kinematic model of the mobile robot (3), that is to say, $\dot{\mathbf{h}}(t) = f(\mathbf{h})\mathbf{v}(t)$, Therefore, the following control law is proposed,

$$\mathbf{v_c} = \mathbf{J^{-1}}\left(\dot{\mathbf{h}}_\mathbf{d} + \mathbf{Ktanh}\left(\tilde{\mathbf{h}}\right)\right) \tag{8}$$

where, $\dot{\mathbf{h}}_\mathbf{d} = \left[\dot{h}_{dx}\ \dot{h}_{dy}\right]^T$ represents the reference speeds of the mobile robot; $\mathbf{J^{-1}}$ is the inverse matrix of the mobile robot's kinematics; while $\mathbf{K} > 0$ are positive diagonal gain matrices; $\tilde{\mathbf{h}} = \left[\tilde{h}_x\ \tilde{h}_y\right]^T$ represent the control errors; finally an analytical velocity saturation is included with the $\mathbf{tanh}(.)$ that limits the error $\tilde{\mathbf{h}}$.

However, the behavior of control errors $\tilde{\mathbf{h}} = \mathbf{h_d} - \mathbf{h}$ are analyzed considering a perfect speed tracking, *i.e.,* $\mathbf{v}(t) \equiv \mathbf{v_c}(t)$. Replacing (8) in (3) the closed-loop equation is obtained $\dot{\tilde{\mathbf{h}}} + \mathbf{K}\tanh\left(\tilde{\mathbf{h}}\right) = \mathbf{0}$. For stability analysis, the Lyapunov candidate function defined as $\mathbf{V}\left(\tilde{\mathbf{h}}\right) = \frac{1}{2}\tilde{\mathbf{h}}^\mathbf{T}\tilde{\mathbf{h}} > \mathbf{0}$. Its temporal derivative in the system's trajectory is:

$$\dot{V}\left(\tilde{\mathbf{h}}\right) = \tilde{\mathbf{h}}^{\boldsymbol{T}}\mathbf{K}\tanh\left(\tilde{\mathbf{h}}\right) < 0 \tag{9}$$

What the closed-loop system implies is asymptotically stable, so that the positioning error of the robots $\tilde{\mathbf{h}}(t) \to 0$ is asymptotically stable with $t \to \infty$.

5.3 Dynamic Compensation of the I-th Robot

On the other hand, if perfect speed tracking is not considered in the design of the kinematic controller, *i.e.,*$\mathbf{v}(t) \neq \mathbf{v_c}(t)$, the speed error is defined as $\tilde{\mathbf{v}}(t) = \mathbf{v_c}(t) - \mathbf{v}(t)$. Considering this speed error arises the need to design a dynamic compensation control, whose objective is to reduce the speed tracking error; therefore, it is proposed the following control law based on the dynamic model (4), [15, 17]

$$\mathbf{v_{ref}} = \mathbf{M}(\varsigma)(\dot{\mathbf{v}}_\mathbf{c} + \mathbf{Ktanh}(\tilde{\mathbf{v}})) + \mathbf{C}(\varsigma, \mathbf{v})\mathbf{v} \tag{10}$$

where, $\mathbf{v_{ref}} = \left[u_{ref}\ \omega_{ref}\right]^T$ represent the control actions; $\dot{\mathbf{v}}_\mathbf{c} = \left[\dot{u}_c\ \dot{\omega}_c\right]^T$ represent the kinematic control accelerations; finally, an analytical speed saturation is included with the function. $\mathbf{tanh}(.)$ that limits the error $\tilde{\mathbf{v}}$.

A Lyapunov candidate function and its temporal drift are then introduced into the system trajectories to perform the stability analysis $\mathbf{V}(\tilde{\mathbf{v}}) = \frac{1}{2}\tilde{\mathbf{v}}^T\tilde{\mathbf{v}}$. The temporal derivative of Lyapunov's candidate function is:

$$\dot{\mathbf{V}}(\tilde{\mathbf{v}}) = \tilde{\mathbf{v}}^T\dot{\tilde{\mathbf{v}}} \tag{11}$$

After introducing the control laws (4) and (10) in (11), the time derivative can be expressed as:

$$\dot{\mathbf{V}}(\tilde{\mathbf{v}}) = -\tilde{\mathbf{v}}^T\mathbf{K}_1\tanh(\tilde{\mathbf{v}}) < 0 \tag{12}$$

For the stability of the proposed control law, with $\mathbf{K}_1 > 0$, it is possible to guarantee that $\tilde{\mathbf{v}}(t) \to 0$ is asymptotically when $t \to \infty$.

6 Experimental Results

This section presents the experimental results of the HIL scheme implemented for the formation control of three unicycle-type robots. For the execution of the different tests of experimentation it was considered a computer in which it was implemented the algorithm of centralized control of formation of the three mobile robots. While, the decentralized control of each robot and kinematic and dynamic models were implemented in embedded devices, known as Raspberry Pi 4., see Fig. 6. This decentralized control consists of kinematic models represented by (3) and dynamic, represented by (4) where the values of $\varsigma_1 = 0.1951$, $\varsigma_2 = 0.2231$, $\varsigma_3 = -0.0006$, $\varsigma_4 = 1.0015$, $\varsigma_5 = 0.0027$, $\varsigma_6 = 0.9723$, $\varsigma_7 = -0.0004$ and $\varsigma_8 = -0.0554$ were found based on experimental tests performed on the mobile robots available at the research laboratory in automation, robotics and intelligent systems (ARSI)

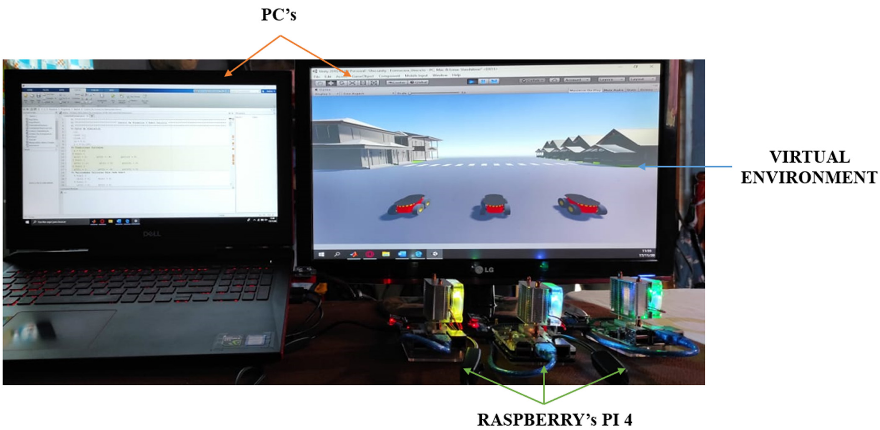


Fig. 6. Implementation of formation control in HIL environments

In addition, it is important to mention that for the virtualization of the robots' movements a 3D virtual environment was developed, see Fig. 7. In the virtual environment was incorporated physical characteristics of the real world, *e.g.,* gravity; friction forces of tires with different soil types; audio data, and other properties that simulate a real environment so as to allow the evaluation of different control algorithms.

i. First Experiment

The first experiment consists of executing the formation of three unicycle-type robots. The desired trajectory for this formation is described with: $x_{do} = 0.1t$ and $y_{do} = 2\sin(0.1t)$. Figure 8 shows the strobe movement of the trajectory execution (x_{do} and y_{do}) in which it can be observed that the movement of the robots satisfactorily fulfills the desired task, so much in orientation and distance, it is to say that the primary robot it was maintained in the path desired, the same as the second and third robot.

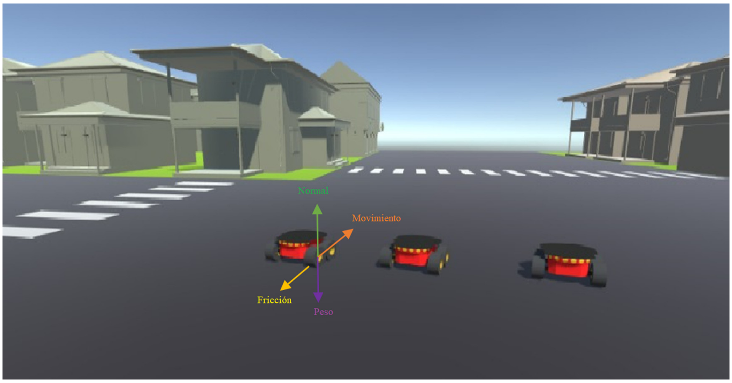


Fig. 7. Virtual environment developed for the formation of mobile robots

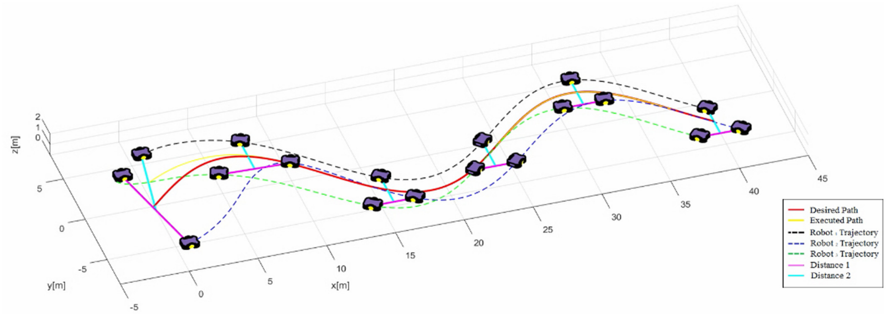


Fig. 8. Formation path, executed by unicycle type robots.

Below are the errors (see Fig. 11) obtained in the execution of the trajectory (x_{do} and y_{do}) of each one of the robots type unicycle considering a null disturbance, in addition it is evident that the errors have a suitable behavior since its magnitude is almost negligible is ideal since it is concentrated in the proximities of zero (Fig. 9).

ii. Second Experiment

In this section, both position and orientation errors obtained in the same desired path are shown (see Fig. 8). Where it can be detailed that, to the beginning of the experiment, it was produced a considerable error caused by the initial positions of each robot. By means of the implementation of the control of formation, it was found the point more near to the path, where the robots it was placed of way that the position of the main robot it was in the path desired and therefore the remaining realized it same (Fig. 10).

It is necessary to emphasize that, for the developed experiment, the control of formation has as purpose to generate speeds of reference that, through the kinematic control, each robot followed a path, the same that contributes to find the expected formation.

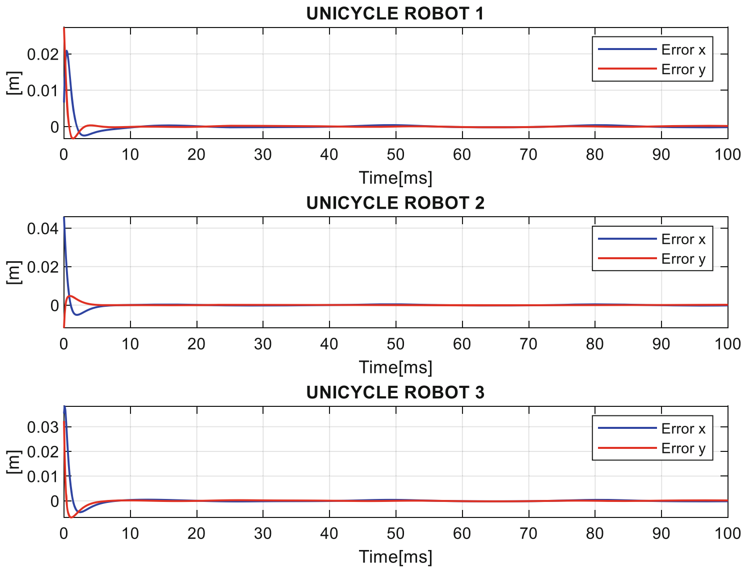
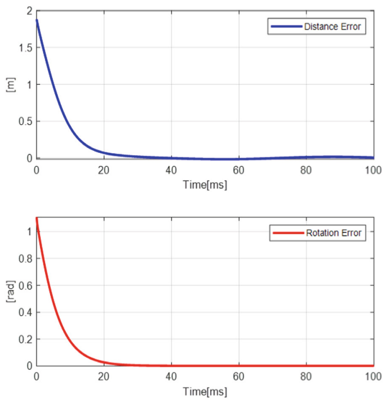
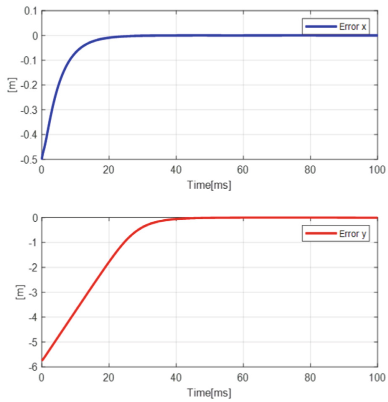


Fig. 9. Errors presented in each robot immersed in the formation system.



a) Orientation errors.



b) Position errors.

Fig. 10. Errors presented in the formation system at the point of interest (orientation and position).

iii. Third Experiment

In this section, they are presented the errors (see Fig. 11) obtained of each one of the robots type uniciclo in the trajectory already mentioned taking in consideration a disturbance in the dynamics of the same ones, where it refers to the interaction among the tires of the robot and the type of floor that is to say the force of friction that is generated among them, producing this way a representative error of speeds, but in turn these errors are limited in the neighborhoods of zero.

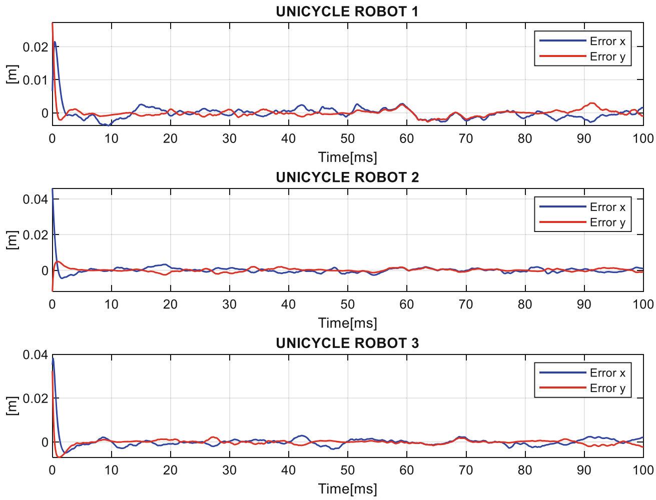


Fig. 11. Errors presented in each robot immersed in the formation system applying disturbances.

7 Conclusion

The control of formation in environments HIL that considers distance, position and angle is achieved through signals of reference emitted to the independent structures of each robot, for it three robots type unicycle were used the same ones that in turn, contributed to the evaluation of the performance of the controller implemented in this proposal in comparison to other more complex and expensive controls, that is to say, the pursuit of the trajectory for the robotic set, In addition, by means of the analysis of stability of the law of control it is de-shown that the system is asymptotically stable maintaining the errors in the proximities of zero. This work employs for its operation the processing of centralized and decentralized tasks so that a computer calculates the position, distance and angle of the path, while the processing units ensure the kinematic control added a dynamic compensation of each robot independently. Finally, it simulates the set of robots used a virtual environment to obtain the experimental results, results that demonstrate the proper functioning of the proposed controller in HIL environments for the three mechanisms. All the mentioned can be applied in different areas, sectors and strategic places oriented to collaborative tasks.

Acknowledgements. The authors would like to thank the Corporación Ecuatoriana para el Desarrollo de la Investigación y Academia-CEDIA for their contribution in innovation, through the CEPRA projects, especially the project CEPRA-XIV-2020-08RVA "Tecnologías Inmersivas Multi-Usuario Orientadas a Sistemas Sinérgicos de Enseñanza y Aprendizaje"; also the Universidad de las Fuerzas Armadas ESPE, Escuela Superior Politécnica de Chimborazo, Universidad Técnica de Ambato, Universidad tecnológica Indoamérica and the ARSI Research Group, for the support for the development of this work.

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