People-following System with Mobile Robot using Delayed Controllers

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***Abstract*—This article describes a delay-based application using Proportional Retarded controllers for a person-following system with a mobile robot. The tuning strategy for person-following with mobile robot consists in the distance and angle closed-loop controls assigning a triple real dominant root that corresponds to the maximum achievable exponential decay. The distance and angle are measured on the transverse and longitudinal axes of the Kinect v2 with infrared vision time of flight depth system. The sensor is mounted on the mobile robot and is used as feedback sensor. Real-time experiments are presented to verify control performances of the Proportional Retarded and Proportional Derivative controllers.**

***Keywords*— proportional retarded controller, nonholonomic restrictions, mobile robot, person following, delay.**

I. Introduction

In recent years, authors have worked with following control with mobile robots and people. These authors have applied control techniques through backstepping, and cascade system theory used in [1] to control multiple robots and the method is complemented by a bioinspired dynamic to avoid impractical velocity jumps [2], the backstepping is merged with a fuzzy control strategy in [3] and they have used a discrete model using distance and angle [4].

This problem of people-following has been solved with mobile robots using cameras and lasers [1], [4], [5]. However, some works have needed to process color detection and segmentation, where system requires to be robust on noisy environments. The goal is implemented a person-following system with a mobile robot, where it can track and follow a moving person using the distance and angle given by Kinect. This can measure the variables with infrared vision time of flight depth system, also, Kinect is used as feedback sensor. However, the mentioned strategies are more complex in design, mathematical analysis, and implementation. In this work the first proposed strategy is by the Proportional Derivative control [6], [7], where one of the main problems is tuning the derivative term, which may amplify high-frequency measurement noise using velocity estimates obtained from a high-pass filter [6], thus precluding the use of high values of derivative gains.

Then, the solution is inspired and solved by previous contribution using controllers with delays [8], where the noise attenuation and the disturbance rejection are retained. The Proportional Retarded controller has been a research subject in [9] and [10], and recently it has been implemented in vibration mitigation control [11] or combined with an integral action [12] and the cascade proportional integral [13]. Compared with the Proportional Derivative (PD) controller, the Proportional Retarded (PR) [8] algorithm does not seek to estimate the time-derivative, the method provides simple tuning formulae, and the performance of the PR closed-loop control has been compared with a PD closed-loop control using DC servomotors, robots, underactuated systems, among others.

The paper layout is as follows: section II describes the kinematic model with the Kinect sensor, its distance and angle measurements using Proportional Retarded controls. Section III presents the Proportional Retarded controllers implementation and Section IV is devoted to real-time experiments. Finally, Section V concludes this paper.

II. Modeling Issues

A. Kinematic model of mobile robot

The mobile robot used for this work is a robot type 2.0, that it is represented in Figure 1:

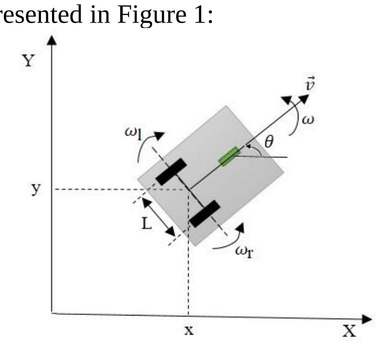

Figure 1. Diagram of mobile robot.

where the kinematic model of this robot is given by [14]:

$$\dot{x} = v\cos(\theta)$$
$$\dot{y} = v\sin(\theta) \quad (1)$$
$$\dot{\theta} = \omega$$

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where x and y are the positions along the axis X and Y, respectively, θ corresponds to the orientation angle and ω is the angular velocity of the mobile robot. The linear and angular velocities of each robot are related to the angular velocity of the right wheel ω_r and the angular velocity of the left wheel ω_l, by means of the relation:

$$v = \frac{r\left(\omega_r + \omega_l\right)}{2}$$
$$\omega = \frac{r\left(\omega_r - \omega_l\right)}{L} \qquad (2)$$

where r is the wheel ratio and L is the distance between the wheels. The control of nonholonomic mobile robots is not considered in this work, however, it is important to consider that a mobile robot has the next restrictions nonholonomic [14], where $\dot{\varphi}_l$, $\dot{\varphi}_r$ are the velocities of the center of each wheel:

$$-\dot{x}\sin(\theta) + \dot{y}\cos(\theta) = 0$$
$$\dot{x}\cos(\theta) + \dot{y}\sin(\theta) - L/2\,\dot{\theta} = r\dot{\varphi}_l \qquad (3)$$
$$\dot{x}\cos(\theta) + \dot{y}\sin(\theta) + L/2\,\dot{\theta} = r\dot{\varphi}_r$$

when $\theta \to 0$, the equations (3) are redefined as $\dot{y} = 0$, $\dot{x} = r\dot{\varphi}_l$ and $\dot{x} = r\dot{\varphi}_r$. Also, the system (2) is rewrited as:

$$\begin{pmatrix} v \\ \omega \end{pmatrix} = \begin{pmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{L} & -\frac{r}{L} \end{pmatrix} \begin{pmatrix} \omega_r \\ \omega_l \end{pmatrix}. \qquad (4)$$

However, when it is considered the kinematic model with Kinect sensor variables, namely, its distance and angle measurements, we must apply a change of variables between the mobile robot and Kinect sensor as it is shown in Figure 2.

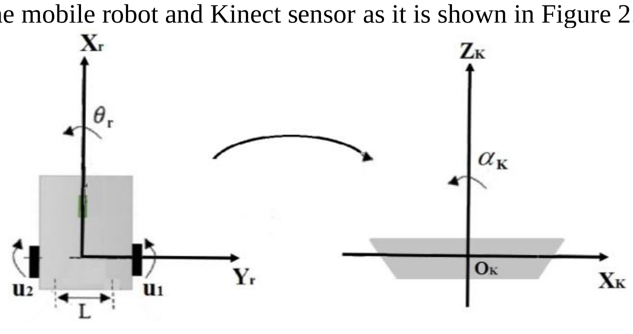

Figure 2. Change of variables between the mobile robot and Kinect sensor.

where d and α are defined as its degrees of freedom, and these are estimated respect to the point P_r of the person by Kinect sensor (see Figure 3):

$$d = \sqrt{{Z_k}^2 + {X_k}^2} \qquad (5)$$

$$\alpha = \sin^{-1}\left(\frac{X_k}{\sqrt{{Z_k}^2 + {X_k}^2}}\right). \qquad (6)$$

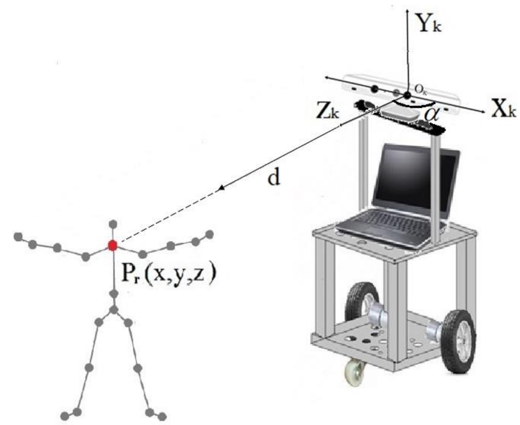

Figure 3. Variables d and α obtained with Kinect v2 for the person-following system.

Also, it is possible to obtain a model of mobile robot utilizing the variables of the Kinect sensor determined by (7):

$$\begin{pmatrix} \dot{d} \\ \dot{\alpha} \end{pmatrix} = \begin{pmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{L} & -\frac{r}{L} \end{pmatrix} \begin{pmatrix} \omega_r \\ \omega_l \end{pmatrix} \qquad (7)$$

Consequently, the model (7) has two degrees of freedom and depends from the speeds of the right and left motor where the control strategies will be inserted to apply control strategy. So, applying a change of variable to have the following representation:

$$\begin{pmatrix} \dot{d} \\ \dot{\alpha} \end{pmatrix} = \begin{pmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{L} & -\frac{r}{L} \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \qquad (8)$$

where u_1 and u_1 are the control inputs to perform follow-up control. Now, it can propose a controller to solve the people-following problem.

B. *Proportional Retarded Controllers*

A typical controller used on Automatic Control is the Proportional Derivative (PD). This controller has been applied to mechanical, electrical robotics systems, among others. A practical problem with the PD controller when applied to control system is the fact that in some situations is not possible to measure the angular velocity. A simple way of overcoming velocity measurements is to use a high-pass filter. Considering the model (8) of the mobile robot we can apply a standard PD, where it estimates the velocities $\dot{d}$ and $\dot{\alpha}$ with the Kinect sensor using a high-pass filter. However, the closed loop system presents noise effect when these parameters are estimated and when these are used high values of derivative gains.

$$u_1 = -k_{P_d} d(t) - k_{D_d}\dot{d}(t) - k_{P_\alpha}\alpha(t) - k_{D_\alpha}\dot{\alpha}(t)$$
$$u_2 = -k_{P_d} d(t) - k_{D_d}\dot{d}(t) + k_{P_\alpha}\alpha(t) + k_{D_\alpha}\dot{\alpha}(t) \qquad (9)$$

In the equations (9) $\alpha(t), d(t)$ are angle and distance measurements on the transverse and longitudinal axes of the Kinect v2 with infrared vision time of flight depth system of the person. However, the first proposal is not effective, so we resort to the design of two Proportional Retarded controllers as it is presented in Figure 4.

$$\begin{aligned} u_1 &= -k_{p_d} d(t) + k_{r_d} d(t-h_1) - k_{p_\alpha}\alpha(t) + k_{r_\alpha}\alpha(t-h_2) \\ u_2 &= -k_{p_d} d(t) + k_{r_d} d(t-h_1) + k_{p_\alpha}\alpha(t) - k_{r_\alpha}\alpha(t-h_2) \end{aligned} \tag{10}$$

where k_{p_d}, k_{p_α} are the distance and angle proportional gains, k_{r_d}, k_{r_α} are the distance and angle retarded gains and h_1, h_2 are delays, respectively.

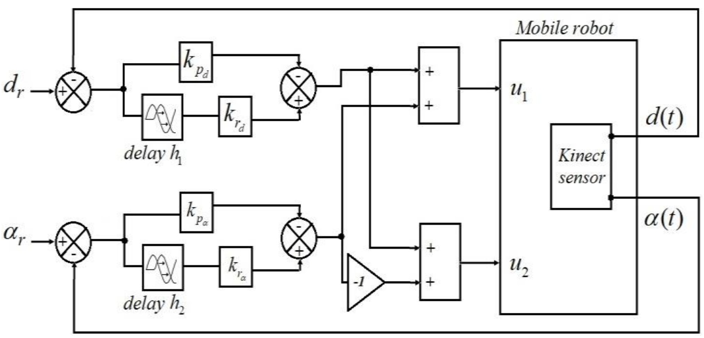

Figure 4. PR controls scheme Kinect as feedback sensor.

Substituting the PR control law (10) into (8) gives:

$$\begin{aligned} \dot{d}(t) &= r\left[-k_{p_d} d(t) + k_{r_d} d(t-h_1)\right] \\ \dot{\alpha}(t) &= \frac{r}{L}\left[-2k_{p_\alpha}\alpha(t) + 2k_{r_\alpha}\alpha(t-h_2)\right] \end{aligned} \tag{11}$$

Now, defining the state variables $x_1(t) = d(t)$, $x_2(t) = \alpha(t)$, $x(t) = \left[d(t)\,\alpha(t)\right]^T$ allow to obtain the following state space representation of the closed loop systems:

$$\dot{x}(t) = A_0 x(t) + A_1 x(t-h) \tag{12}$$

$$A_0 = \begin{bmatrix} -rk_{p_d} & 0 \\ 0 & -\frac{2r}{L}k_{p_\theta} \end{bmatrix}, A_1 = \begin{bmatrix} rk_{r_d} & 0 \\ 0 & \frac{2r}{L}k_{r_\theta} \end{bmatrix}$$

whose characteristic quasipolynomial corresponds to $\det(sI - A_0 - A_1 e^{-sh})$:

$$\begin{aligned} p(s, k_{p_d}, k_{r_d}, k_{p_\alpha}, k_{r_\alpha}) &= s^2 + (rk_{p_d} + \frac{2r}{L}k_{p_\alpha})s \\ &- (rk_{r_d} + \frac{2r}{L}k_{r_\alpha})se^{-sh} + \frac{2r^2}{L}k_{p_\alpha}k_{p_d} \\ &- (\frac{2r^2}{L}k_{r_\alpha}k_{p_l} + \frac{2r^2}{L}k_{r_l}k_{p_\alpha})e^{-sh} + \frac{2r^2}{L}k_{r_\alpha}k_{rl}e^{-2sh} = 0 \end{aligned} \tag{13}$$

Thus, it is used the σ-stability of linear delay systems can be characterized in the frequency domain, where all the roots of the characteristic equation must have real parts smaller than $-\sigma$, as it is proved in [14]. The tuning of the PR controllers to person-following with mobile robot consists of two steps. First, the PR distance closed-loop controller for distance and the second step a PR angle closed-loop controller. This analysis requires to apply a change of variable $s \rightarrow s - \sigma$ and considers that $k_{p_\alpha} = 0, k_{r_\alpha} = 0$. Then, when the distance control is activated for the equation (13) implies that:

$$\begin{aligned} p(s, k_{p_d}, k_{r_d}, 0, 0) &= (s-\sigma_1)^2 + rk_{p_d}(s-\sigma_1) \\ &- rk_{r_d}(s-\sigma_1)e^{-h_1(s-\sigma_1)} = 0 \end{aligned} \tag{14}$$

The next step is defined when $k_{p_d} = 0, k_{r_d} = 0$, where the angle control is activated. Thus, we obtained the next characteristic quasipolynomial

$$\begin{aligned} p(s, 0, 0, k_{p_\alpha}, k_{r_\alpha}) &= (s-\sigma_2)^2 + \frac{2r}{L}k_{p_\alpha}(s-\sigma_2) \\ &- \frac{2r}{L}k_{r_\alpha}(s-\sigma_2)e^{-h_2(s-\sigma_2)} = 0 \end{aligned} \tag{15}$$

Therefore, the analysis is reduced to analyze the characteristic quasipolynomials (14) and (15), that they correspond to the distance and angle controllers between the mobile robot and the person.

C. *Triple Dominant Real Roots Assigment*

As the quasipolynomials (14) and (15) roots behavior in the complex plane is continuous with respect to continuous changes of the coefficients and time delay [15], loss of σ-stabilizability occurs when the quasipolynomials has roots either at $s = 0$ or a pair of pure imaginary roots as $s = \pm j\omega$ and the root crossings of the imaginary axis, which are candidate stability or instability boundaries. The analysis of the previous section motivates the following design assigning a triple root $-\sigma_1^*$ when k_{p_d} is fixed, the corresponding retarded gain $k_{r_d}^*$ and delay h_1^* are also determined.

Lemma 1. Let the proportional gain of the distance control $k_{p_d} > 0$ is given, then, a triple rightmost root of the system (15) at $-\sigma_1^*$ is achieved for:

$$\sigma_1^* = 2rk_{p_d} \tag{16}$$

Moreover, the values of delayed gain $k_{r_d}^*$ and delay h_1^* that σ-stabilize to (14) lineally with the exponential decay.

$$h_1^* = \frac{-1}{rk_{p_d} - \sigma_1^*} \quad (17)$$

$$k_{r_d}{}^* = \frac{rk_{p_d} - \sigma_1^*}{re^{h_1^*\sigma_1^*}} \quad (18)$$

Proof 1: When there is a triple root at $-\sigma_1^*$, the conditions $p_{\sigma_1}(0, k_{p_d}, k_{r_d}, 0, 0) = 0$, $\frac{\partial}{\partial s} p_{\sigma_1}(0, k_{p_d}, k_{r_d}, 0, 0)|_{s=0} = 0$ and $\frac{\partial^2}{\partial^2 s} p_{\sigma_1}(0, k_{p_d}, k_{r_d}, 0, 0) = 0$ hold, namely

$$\sigma_1^2 - rk_{p_d}\sigma_1 + rk_{r_d}e^{h_1\sigma_1}\sigma_1 = 0 \quad (19)$$

$$-2\sigma_1 + rk_{p_d} - rk_{r_d}e^{h_1\sigma_1} - h_1 rk_{r_d}e^{h_1\sigma_1}\sigma_1 = 0 \quad (20)$$

$$2 + h_1^2 rk_{r_d}e^{h_1\sigma_1}\sigma_1 = 0 \quad (21)$$

It follows from (19) and (20) that

$$h_1 = \frac{-2\sigma_1 + rk_{p_d} - rk_{r_d}e^{h_1\sigma_1}}{rk_{p_d}\sigma_1 - \sigma_1^2} \quad (22)$$

And from (19) and (21) imply:

$$h_1^2 = \frac{-2}{rk_{p_d}\sigma_1 - \sigma_1^2}. \quad (23)$$

Substituting the equation (20) into (21) it is possible to obtain to (16). Then (17) is estimated from substituting (16) into (20), and the equation (18) is calculated from (19). Now, the analysis of the previous section motivates the following design assigning a triple root $-\sigma_2^*$ when k_{p_α} is fixed, the corresponding retarded gain $k_{r_\alpha}{}^*$ and delay h_2^* are also determined.

Lemma 2. Let the proportional gain of the angle control $k_{p_\alpha} > 0$ is given, then, a triple rightmost root of the system (13) at $-\sigma_2^*$ is achieved for

$$\sigma_2^* = \frac{4r}{L}k_{p_\alpha} \quad (24)$$

Also, the values of delayed gain $k_{r_\alpha}{}^*$ and delay h_2^* that σ -stabilize to (15) lineally with the exponential decay σ_2^* are defined as:

$$h_2^* = \frac{-1}{\frac{2r}{L}k_{p_\alpha} - \sigma_2^*} \quad (25)$$

$$k_{r_\alpha} = \frac{\frac{2r}{L}k_{p_\alpha} - \sigma_2^*}{\frac{2r}{L}e^{h_2^*\sigma_2^*}} \quad (26)$$

Proof 2: Applying the conditions of the Proof 1.

$$\sigma_2^2 - \frac{2r}{L}k_{p_\alpha}\sigma_2 + \frac{2r}{L}k_{r_\alpha}e^{h_2\sigma_2}\sigma_2 = 0 \quad (27)$$

$$-2\sigma_2 + \frac{2r}{L}k_{p_\alpha} - \frac{2r}{L}k_{r_\alpha}e^{h_2\sigma_2} - h_2\frac{2r}{L}k_{r_\alpha}e^{h_2\sigma_2}\sigma_2 = 0 \quad (28)$$

$$2 + h_2^2\frac{2r}{L}k_{r_\alpha}e^{h_2\sigma_2}\sigma_2 = 0 \quad (29)$$

The result follows from straightforward algebraic manipulations of (27)-(29). The tuning methodology has its roots in the D-subdivisions method proposed in [16], the idea behind the tuning is to divide the parameter space into disjoint regions separated by stability boundaries. The above allows identifying in the plane a triple root corresponding to the maximum exponential decay rate σ of the closed loop system.

III. Experimental Results

The experiments are developed using the PR controllers of the mobile robot for the evaluation of the dominant real roots assignment. The employed mobile robot for the experiment has a DC motor controlled through a RoboClaw Target, this is configured in velocity mode. Each motor has an integrated optical encoder directly that gives angular position, the resolution of the optical encoder is 5000 pulses per revolution. The Kinect v2 is used as sensor, which can track a person and the Matlab2012b-Simulink-QuaRC graphical programming together with QuaRC Quanser real-time environment that allows the development of the controller proposed.

The mobile robot is shown in Figure 5, it contains: 1) Kinect sensor v2, 2) Dell Mobile Precision M4700 computer, 3) Matlab-Simulink-QuaRC and Visual Studio, 4) RoboClaw motor controller, 5) Mechanic structure, pneumatic wheels, and support wheel, 6) Direct Current (DC) motors, 7) Encoders E3 and 8) Lithium battery.

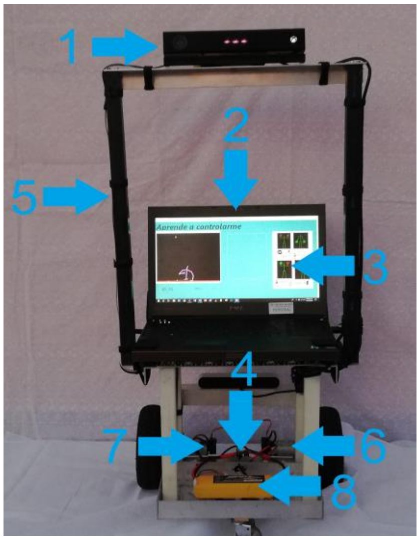

Figure 5. Mobile robot experimental.

The mobile robot was developed with the Computer M4700, where it carries through two programs of operation with the software Matlab2012b-Simulink-QuaRC 2.3, Visual

Studio V.12 (C#) and Kinect Studio Software Development Kit (SDK V2). Mostly, the processor runs two tasks: graphic interface of Kinect was developed in C# and real-time control in Matlab2012b-Simulink-QuaRC. The mobile robot parameters for these experiments are $r = 0.0625$ m for the ratio and $L = 0.45$ m for the distance between the wheels.

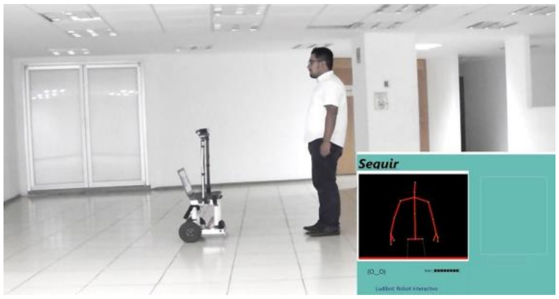

Figure 6. User utilizing mobile robot with person-following system.

Table 1 shows the parameters used in the experiments using PR controls, both controllers are tuned considering the same value of σ_1 and σ_2, and Figure 7 shows the dominant roots corresponding to σ-stability.

PR	k_{p_d}	k_{r_d}	σ_1	h_1
	15	-2.0304	4.5	0.4444
	k_{p_α}	k_{r_α}	σ_2	h_2
	0.5	-0.0676	0.75	2.6666

Table 1. Parameters for PR controllers.

The gains for PD controllers are selected with respect to k_{p_d} and k_{p_α}, i.e., these gains were fixed using PR and the derivative gains were adjusted experimentally as it is shown in the Table 2. The values of the pairs (k_{P_d}, k_{D_d}) and (k_{P_d}, k_{D_d}), which correspond the gains range. The experiment with PD controllers was carried out with (15, 1) and (0.5, 0.1) gains. If we chose gains below these, the steady-state error increment, in contrast, when we use high values of gains, a high level of noise, disturbances and oscillations are inserted to the system.

PD	k_{P_d}	k_{D_d}	k_{P_ω}	k_{D_ω}
	1	0.1	0.1	0.01
	2.5	0.25	0.25	0.05
	5	0.3	***0.5***	***0.1***
	7.5	0.4	0.75	0.12
	10	0.5	1	0.15
	12.5	0.75	1.25	0.175
	15	***1***	1.5	0.2
	17.5	1.25	1.75	0.25
	20	1.5	2	0.3

Table 2. Parameters for PD controllers.

Figure 8 and Figure 9 show the response of the mobile robot under both control schemes, where the distance and angle reference are fixed and the errors serve as a performance of the following quality, the error measurements show that PR controls present a better following when PR controllers consider a distance and an angle fixed than PD controls.

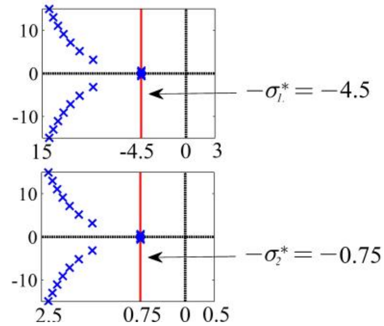

Figure 7. Dominant roots corresponding to σ_1 and σ_2

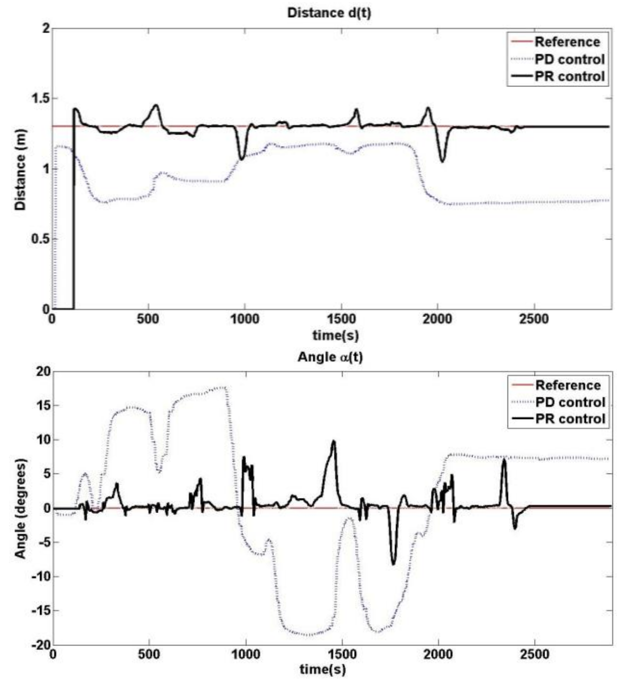

Figure 8. Distance and angle responses of the mobile robot in closed loop with PD and PR controllers.

A further advantage of the proposed controllers is shown in Figure 8, where a smooth control signal is produced by the PR controllers, in contrast, the PD control signals show a noisy control signal produced by the PD although $\dot{d}, \dot{\alpha}$ the distance and angle derivative are estimated through a high pass filter applied to person following system. It is important to mention that the signals in Figures 8, 9 and 10 have an activation delay, because the mobile robot is activated and controlled through a playful interface that depends to the user [17]. Independent tests were carried out for both controllers.

IV. Conclusions

The use of the Proportional Retarded controls can solve satisfactory people-following problem with mobile robot. These results validate the proposed tuning method based on a three real dominant poles assignment corresponding to a desired maximum exponential decay rate. The results reported in this work show that the PR controllers are a promising alternative to the standard PD employed for mobile robot, with three important differences. First, only distance and angle measurements are needed, second, there is no need of velocity estimations or reconstructions which requires the on-line solution of a dynamic system and PR controller has the advantage of simplifying the sensor noise obtaining that the mobile robot solves the problem of people-following.

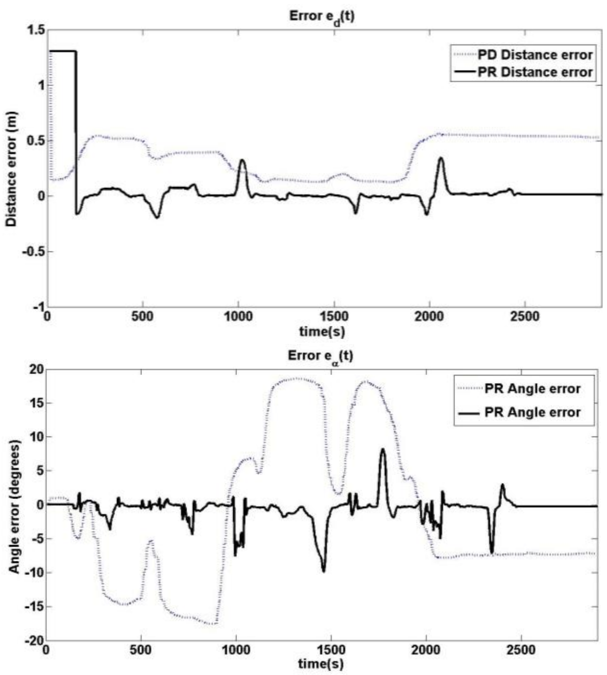

Figure 9. Distance and angle errors of the mobile robot in closed loop with PD and PR controllers.

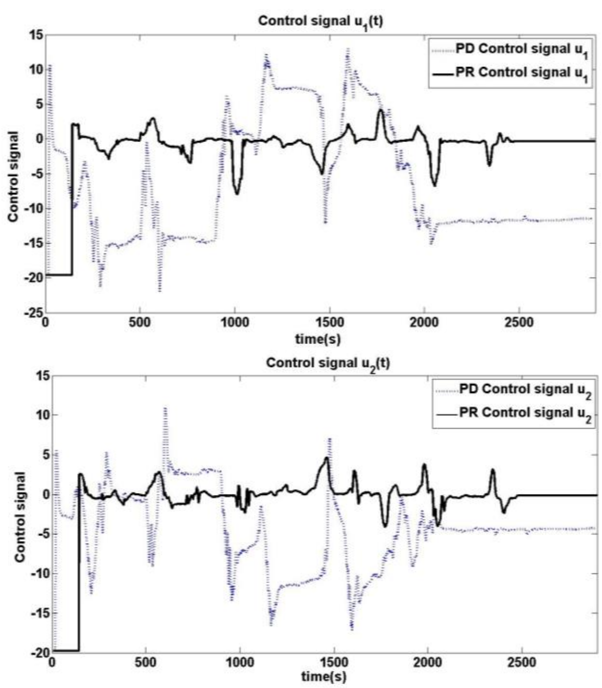

Figure 10. Distance and angle control signals of the mobile robot in closed loop with PD and PR controllers.

This proposal showed efficient results using a PR controller tuning strategy for mobile robot. The simplicity of the PR controller provides an alternative to using the standard PD applied to person following system with mobile robot. Future work includes developing analytical formulae for simultaneously tuning the six parameters of PR controller considering only a delay h and an exponential decay σ. Also, it can apply the tuning methodology by D-subdivisions method using the parameter space.

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