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Two PID-Based Controllers for a tethered Segway on Dome Shaped Structures

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Abstract: **The UTDTR Robot is a human inspired robotic platform based on a two-wheeled mobile robot. This robot is designed for the purpose of dome shaped structures inspection and maintenance, and it is a tethered robot to stably climb steep surfaces on the top of dome structures. In this paper analysis and controller design of this robot modelled as a MIMO system is represented in order to provide the desired performance on the operating surface with minimum control effort and complexity. Two PID-based controllers are designed such that the stability and desired performance conditions are obtained. In the first design a fuzzy PID controller with self-tuning scale factors is designed to tune the controller gains is forwarded, while in the second approach a multi model gain scheduling controller based on conventional PID controller is considered. Finally, the effectiveness and simplicity of the proposed controller is verified through simulation, comparing the resulting closed loop transient and steady-state response to that of the previously proposed controllers.**

Keyword—Dome, Segway, Climbing Robot, PID Control

I. Introduction and Related Works

Climbing steep structures such as dome shaped structures, is an interesting field for robotics and mechatronic researchers working on climbing and service robots. There is a wide range of applications for these climbing robots such as climbing dome-shaped structures for purpose of cleaning, inspection, and maintenance. Dangers and difficulties in cleaning, inspection, and maintenance performed on tall structures such as domes and poles by human workers, has initiated robotic projects with purpose of climbing these structures. Furthermore, limited operation time and high demand for autonomous operations in most of the actions taken on a tall structure, are other important reasons why different robotic teams started working on designing robots to work on these situations from both theoretical and practical points of view. [1]–[6]

Different robotic mechanisms and methods have been used to design and develop platforms in order to climb walls, poles and steep surfaces. Magnetic systems [7]–[9], systems with adhesive materials [10], [11], and suction and vortex [12]–[14]. Based on prescribed difficulties and dangers in human-based climbing methods [6], a team in Advanced Robotic and Intelligent systems (ARIS) laboratory initiated University of Tehran Dome Climbing Robots (UTDCR) as shown in Figure 1. A multi robot platform is designed and implemented. In this mechanism, with three or more robots cooperate with each other to stably maneuver on the structures with both positive and negative slopes [5]. This robotic system is able to cover all parts of a dome, but its complexity in control has become a challenge. Since most damages and dirt take place in the top part of the dome shaped structures where the slope is positive, the top of domes is the most important area to be inspected and maintained, and a robot that can safely cover the top part of a dome is practical enough for most cases. Therefore, a single tethered robot, "UTDTR", inspired from human dome climbers, with purpose of inspection, cleaning and maintenance was firstly implemented, and successfully tested for dome inspection. As it is prescribed in [6] the UTDTR, consists of a simple two-wheeled mobile robot with differential drive locomotion, and a tether mechanism controlling the length of the rope connecting to the top of the dome. It worth to mention that the tether mechanism is placed on the mobile robot to eliminate the gravity force applied to the robot and prevent from falling from the dome's surface.

A two-wheeled mobile robot may be considered as a popular Segway mechanism, where there are lots of work on controlling them. Despite the vast controllers presented for Segways and other two-wheeled mobile robots [15], [16], control and analysis of a system like this tethered Segway on the dome is a novel problem in which a few control structures have been implemented successfully [6], [17], [18]. In [6] static analysis of the prescribed robot has been presented and existence of the stability condition for this robotic platform

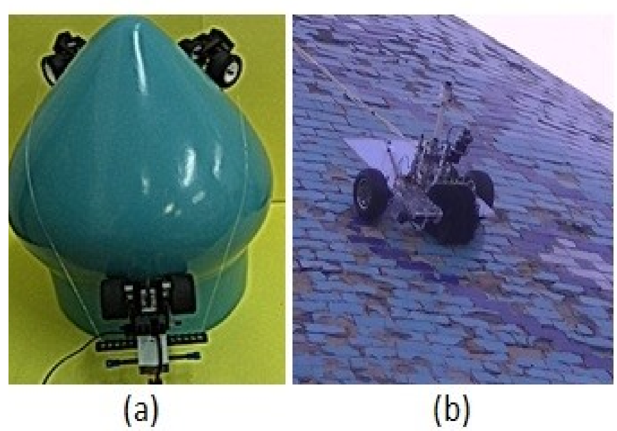

Figure 1. (a) The multi-robot platform to climb the dome-shaped structures. (b) Dome Tethered Robot climbing the dome

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has been mathematically proved with the aid of Lyapunov theorem. In [17] a dynamic model of the robotic system has been derived and a LQR based controller has been developed for the platform in order to obtain desired behavior on the dome. Finally in [18] a robust control system has been designed, simulated and tested based on the previously derived model. In this paper, analysis and controller design of this MIMO system is represented in order to provide the desired robust performance on the operating surface with minimum control effort and complexity. Simple PID-based controllers are considered for this purpose to satisfy the stability and desired performance conditions. Furthermore, gain-scheduling method is used for covering all the dome surface conditions with desired performance. Finally, the effectiveness and simplicity of the proposed controllers are verified through simulation, by comparing the resulting closed loop transient, and steady-state responses to that of the previously proposed controllers.

II. System Description and Model

The "UTDTR" robotic system described in details in [6] is a two-wheeled mobile robot, with a differential derive locomotion method which is equipped with a tether mechanism. The tether mechanism, consists of a pulley, a DC-Motor, and a rope tethering to the top of the dome to provide stability on the steep surface. Figure 2 illustrates a simple schematic of the UTDTR system, in which the system may be considered as a tethered Segway on a dome-shaped structure. Mathematical modeling of the UTDTR system, has been previously derived with aid of Euler–Lagrange equation and reported in [17].

This paper represents the design of model-based controllers for the prescribed system. For this purpose, first the dynamic model of the system is reviewed. Considering the dome as a steep surface with different slopes, it is shown that the UTDTR system may be modeled with a nonlinear time-invariant system with following dynamic equations [17].

$$\ddot{\theta} = f_1(\dot{\theta}, \dot{\phi}, \psi, \dot{\psi}, \theta_d, v_r, v_l) \quad (1)$$

$$\ddot{\phi} = f_2(\dot{\phi}, \psi, \dot{\psi}, v_r, v_l) \quad (2)$$

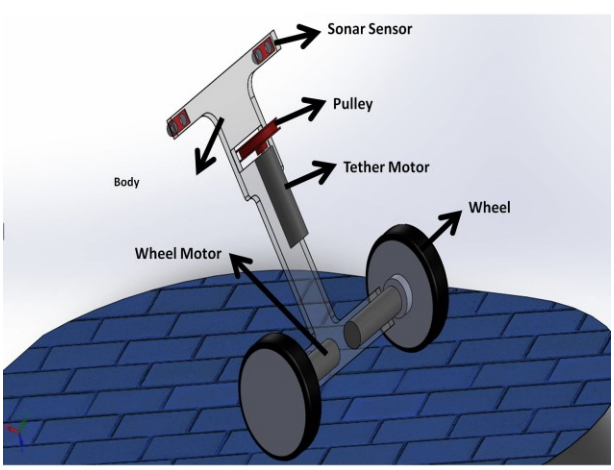

Figure 2. Tethered Segway schematics with a motor controlling the length of the tethered attached to the top of a steep surface.

$$\ddot{\psi} = f_3(\dot{\theta}, \dot{\phi}, \psi, \dot{\psi}, \theta_d, v_r, v_l, v_t) \quad (3)$$

In which, θ, ϕ, ψ represent system's state variables or motion variables of the system. These variables respectively denote the average angle of left and right wheel (which specifies the average straight movement of the robotic platform), body yaw and body pitch angles. Here, v_r, v_l, v_t are system's input signals. These inputs are voltage commands to the DC-motors of the robot actuating the right and left wheel and the tether mechanism. θ_d denotes the slope of the dome which is a varying parameter. This variable is related to the robot's position of the dome and is directly measured on the dome operations. Thus we can simplify these equations as follows:

$$\dot{x} = f(x, u, \theta_d) \quad (4)$$

$$y = [\theta, \phi, \psi]^T \quad (5)$$

where f is a nonlinear function and we have:

$$x = \left[\theta, \dot{\theta}, \phi, \dot{\phi}, \psi, \dot{\psi}\right]^T, u = [v_r, v_l, v_t]^T \quad (6)$$

whose details may be found at the following links: *http://saba.kntu.ac.ir/eecd/aras/files.zip*

III. Proposed Method

In this section we are going to design the controller for the "UTDTR" system. First of all, a brief description of the control method and strategy is proposed then the controller design is represented.

A. Control Strategy

As described before, the UTDTR system is a nonlinear system. In this paper we are going to design simple PID-based controller with minimum complexity and control effort. As this system is a MIMO system with three inputs and three outputs, we may need to decouple inputs in the first step, and then design three PID controllers for each pair of input outputs. Besides, UTDTR's nonlinear behavior is influenced by the dome's slope where the robot is operating on. This variable, i.e. θ_d is measured by a proper sensor, and therefore, information about the dome's slope in different positions on the surface is available. For a better and more robust performance, gain scheduling method is considered for this system. Thus, the controller design would take action in different operating points, and absorption area for each controller would be evaluated based on robust performance of the closed-loop system and low energy consumption. Therefore, the control system is a family of linear controllers, each of which provides satisfactory control for a different operating point of the system.

B. Controller Design

The UTDTR system is an unstable and nonminimum phase system based on simulation and results of [18]. Designing PID controllers to obtain desired performance for a nonminimum-phase and unstable system may encounter serious problems, and therefore, in the first step it is proposed to stabilize the system using a state feedback controller. Using pole placement method suitable state feedback controller gain, K_s is designed. By using this gain in the inner loop a

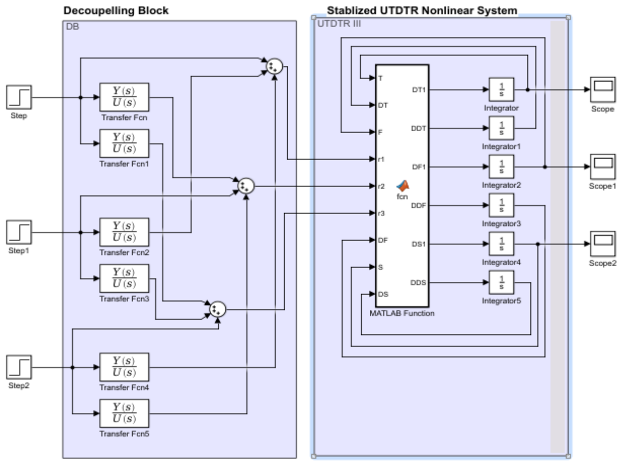

Figure 3. Decoupling block diagram for UTDTR system.

stable plant is obtained which is more continent to design controllers in order to reduce the entropy and sensitivity of the closed-loop system. The dynamic model of the stabilized closed-loop system may be derived using the formulation as follows:

$$u = r - K_s x \tag{7}$$

$$\dot{x} = f(x, r - K_s x, \theta_d) = f_s(x, r, \theta_d) \tag{8}$$

$$y = [\theta, \phi, \psi]^T \tag{9}$$

which is a stable system and we consider system described in (9) as the plant, and design the PID-based gain scheduling controller for this system.

The dome's slope varies from 15° to 75° and the robot's yaw angle is mostly desired to stay around zero. We are going to design a controller to provide both desired steady state and transient response. On the other hand, low value of control effort applied to the robotic platform, i.e. DC motor's terminal voltages is a stringent requirement.

As UTDTR robotic system is a nonlinear system with a variable parameter (dome's slope, i.e. θ_d), the designed controller must be robust to parametric and structured uncertainties of the system. Previously in [18] robust linear controller has been designed to obtain desired performance. In this research we are going to design a self-tuning control PID-based for this MIMO system. In order to perform such, we need to linearize the model and design the controller based on linear approximated model. Let us consider the situation of $\theta_d = 45°$ and $\psi = 0$ as one of the operating points for this platform. By linearizing the stabilized plant results in 3×3 transfer function matrix in a neighborhood about this operating point, RGA [1] analysis on this transfer function matrix can help us to determine appropriate input-output pairing. The RGA matrix for this transfer function matrix is as follows.

$$\text{RGA} = \begin{bmatrix} 0.51 & 0.51 & -0.2 \\ 0.5 & 0.5 & 0 \\ -0.01 & -0.01 & 0.98 \end{bmatrix} \tag{10}$$

As it can be seen, the third input has negligible effect on the first and second outputs, and first and second inputs have almost no effect on the third input. For first two inputs and

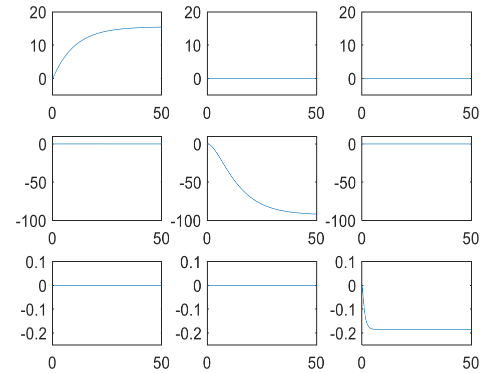

Figure 4. Step response for stabilized decoupled nonlinear system

outputs pairing we can imply that there is no significant difference between these inputs and outputs pairing. Thus, diagonal pairing structure is used for decoupling the plant.

In this block transfer functions used for decoupling the plant are order reduced to second order systems so as the total order of the system is as small as possible. By applying decoupling block as shown in Figure 3, in order to stabilize the plant prescribed in (9), would result to a stable diagonal system. Figure 4 illustrates the step response of the decoupled system.

In order to design the PID controllers first we need to determine the transfer function of the plant after stabilizing and decoupling. In this step we impericaly identify the system instead of analytical calculation of the system model. Estimating the second diagonal element of the resulting transfer function with a fourth order system and the other two elements with third order system, one may find the following transfer matrix of the system.

$$\text{Plant}(s) = \begin{bmatrix} G_{11}(s) & 0 & 0 \\ 0 & G_{22}(s) & 0 \\ 0 & 0 & G_{33}(s) \end{bmatrix} \tag{11}$$

In which:

$$G_{11}(s) = \frac{9.17\,s + 0.24}{s^3 + 6s^2 + 0.75s + 0.015} \tag{12}$$

$$G_{22}(s) = \frac{-1.95s^2 - 2.25s - 3.38}{s^4 + 1.47s^3 + 2.16s^2 + 0.56s + 0.036} \tag{13}$$

$$G_{33}(s) = \frac{-0.67\,s - 0.088}{s^3 + 4.67s^2 + 4.06s + 0.47} \tag{14}$$

Now let us design a PID-based controller for the resulting stabilized, diagonal system for the desired performance. In this paper first a PID type fuzzy controller with self-tuning scaling factors [19] is designed to control the UTDTR system on the steep surfaces with slope $\theta_d \in [15°\ 75°]$. Furthermore, a conventional PID-based controller is designed to evaluate the fuzzy PID controller's performance. To control a decoupled system of the form (11), it is sufficient to control each diagonal element represented in (12-14). Fuzzy PID-controller's block diagram for each diagonal element of the

[1] Relative Gain Array

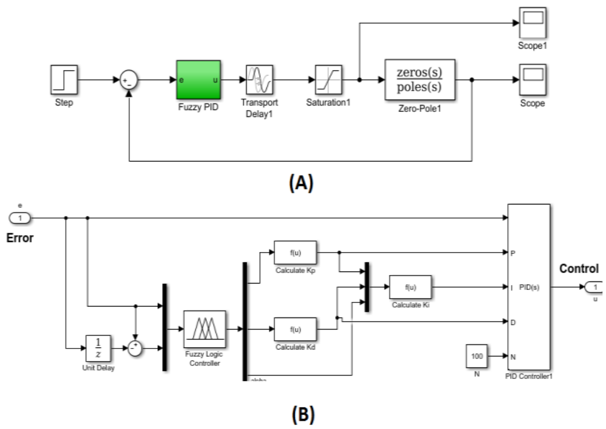

Figure 5. structure of a fuzzy PID controller for SISO system. (B) is detailed block diagram of Fuzzy PID block.

transfer function of the system is illustrated in Figure 5. The colored block represents a Fuzzy PID controller with self-tuning scale factors.

In order to design the fuzzy PID controller a Mamdani-type inference system, with two inputs and three outputs is used. Error of the closed-loop system and rate of change of error are inputs of the inference system. Seven trapezoidal-shaped membership function is used in each input selection, and the triangular ones in the output. Outputs of this inference system are three scaling factors. These factors are numbers in range of $[0, 1]$ and are used to determine parameters of the PID block based on minimum and maximum of each parameter. These boundaries are determined based on parameters of a conventional PID block designed for corresponding plant. Evaluating the PID parameters using these scaling factors and boundaries, for each diagonal element of transfer function matrix of the decoupled system, a MIMO fuzzy PID controller can be developed for the nonlinear system as shown in Figure 6.

For conventional PID-controller design we use the Ziegler-Nichols design rules [20] for each system described in (12-14). Designing proper PID controller for each channel we can form a conventional PID-based controller for UTDTR system. As UTDTR system is a nonlinear parameter variant system, single controller cannot obtain sufficiently good

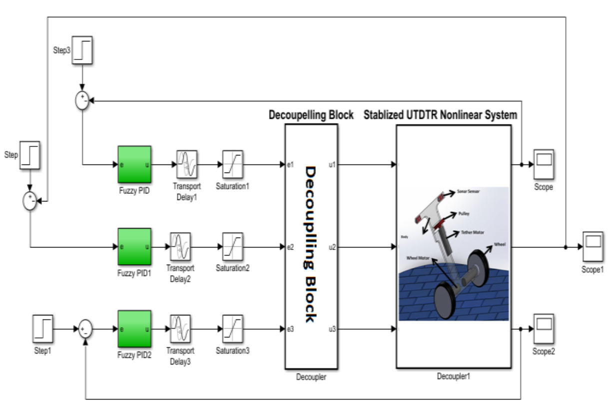

Figure 6. Closed-loop structure for UTDTR robotic system with Fuzzy PID controller.

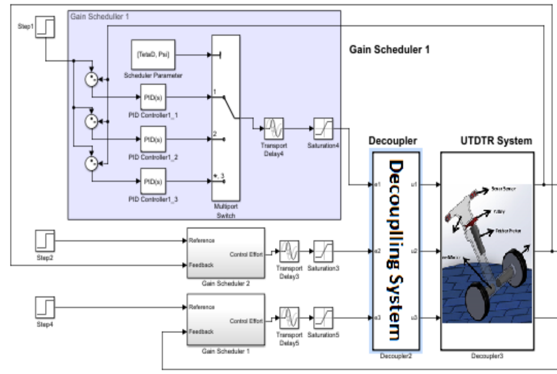

Figure 7. Closed-loop structure for UTDTR robotic system with PID-based gain scheduling controller.

performance. Thus, we design a family of controllers for different operating points of the system and a scheduler to choose proper controller in each condition as shown in Figure 7. The procedure to find number of controllers required to reach desired performance is presented in the following section.

IV. Results and Discussions

In this section results of the closed-loop system applying the designed controllers are reported. Performance of the closed-loop system is evaluated, and absorption area of each controller is specified by closed-loop transient response behavior, steady state response behavior, and control effort applied to the plant. Results of two proposed controllers are compared with each other and with the previously presented controllers.

Figure 8 illustrates the closed-loop response for system represented in Figure 6 for different values of θ_d. Simulations show that the closed-loop system with applied fuzzy PID controller has sufficiently good performance with zero steady state error value and settling time less than three seconds in ψ channel which is the most important channel regarding to the physics of the problem. In nearly horizontal surfaces, i.e. $\theta_d = 15°$ the state variable ψ would reach a peak value of $\psi = 0.33^{rad} \cong 19°$. This value is sufficiently small for system's overshoot based on physical properties of the robot. Control effort of the system is sufficiently small and does not exceed system input limit.

Simulation results show that designing conventional PID controller in three different value of $\theta_d = \{\pi/8, \pi/4, 3\pi/8\}$ provides sufficiently good performance for the closed-loop system. Figure 9 illustrates the result for this system for different values of θ_d. This controller provides zero steady state error value and settling time less than three seconds in ψ channel which is the most important channel regarding to the physics of the problem. In nearly horizontal surfaces, i.e. $\theta_d = 15°$ the state variable ψ would reach a peak value of $\psi = 0.36^{rad} \cong 21°$. This value is still sufficiently small for system's overshoot based on physics of the robot. Control effort of the system is sufficiently small and does not exceed system input limit.

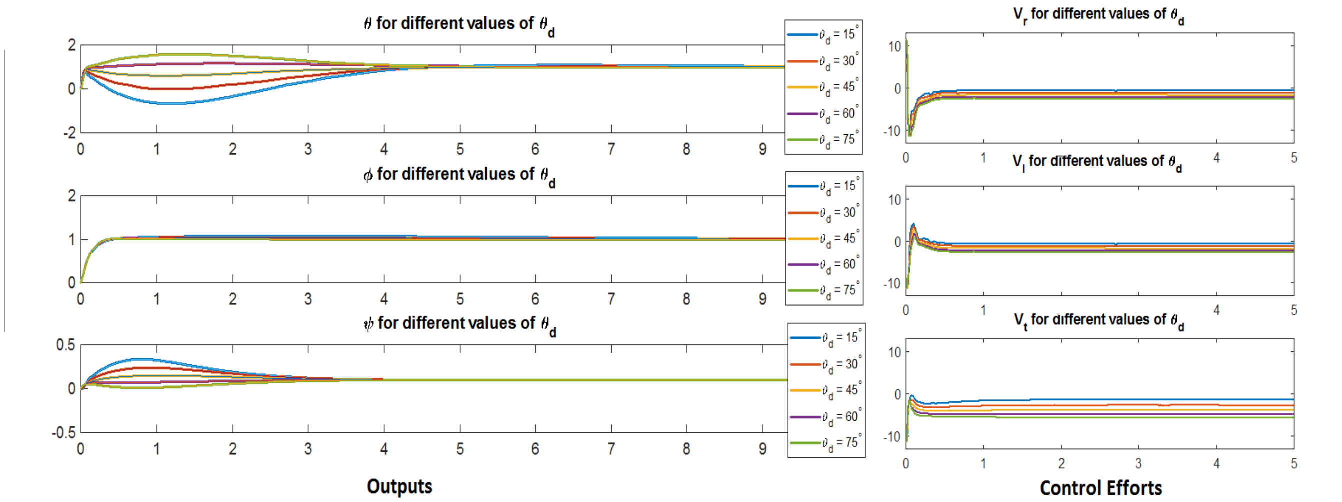

Figure 8. (a) Output for different channels using $fuzzy\ PID$ controller with $self - tuning\ scale\ factors$ in the closed-loop system. (b)Control effort for different inputs, using the $fuzzy\ PID$ controller in the closed-loop system.

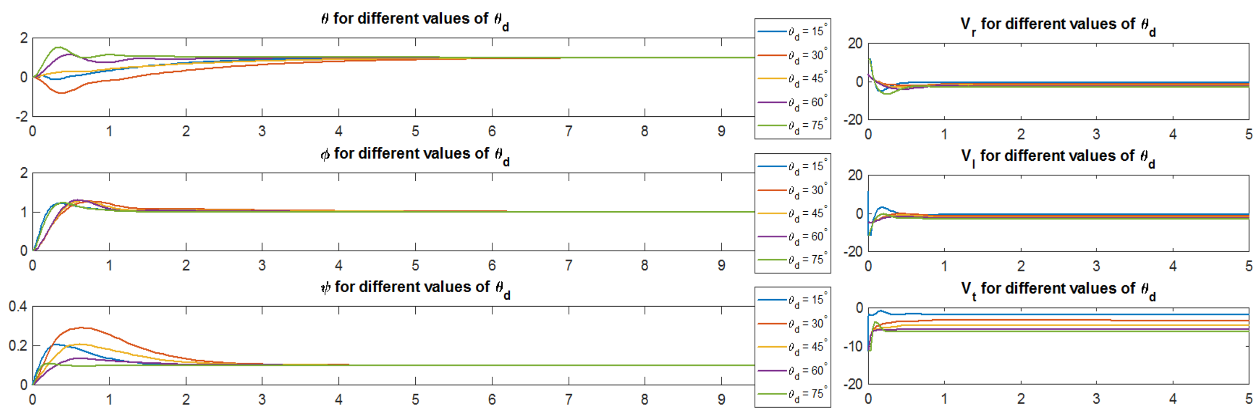

Figure 9. (a) Output for different channels using $PID - based$ gain scheduling controller in the closed-loop system. (b)Control effort for different inputs, using $PID - based$ gain scheduling controller in the closed-loop system.

In order to evaluate these two system's performance let us compare PID-based controllers with the LQR, $H_\infty,\ and\ \mu - synthesis$ controllers previously proposed for the UTDTR system and reported in [17], [18]. In this evaluation, steady state and transient response of the system, level of the control effort applied to the system, and the controller's order and complexity is compared.

A. Controller order and complexity:

In both two cases the controller with the decoupling block in series, is a 3×1 transfer function with fourth order transfer function elements which is a 12th order system, that could be reduced to a fourth order system. The LQR controller increases the closed-loop system's order as systems tracked outputs which is three in case of UTDTR and the robust $H_\infty\ and\ \mu - synthesis$ controllers are respectively sixth and fifth order systems.

B. Steady state response:

Minimum steady state error of the closed-loop system compensated by $H_\infty\ and\ \mu - synthesis$ controllers is $E_{ss_{min}} = 9\%$, but using PID-based controllers designed in this paper and LQR controller this value reduces to $E_{ss} = 0\%$.

C. Transient response:

Transient response of the closed-loop system is evaluated with the maximum overshoot and undershoot of the system and the maximum settling time of the compensated system. simulation results under same conditions and operating points show that PID-based controllers cannot obtain lower maximum overshoot than the robust controllers proposed in [18] but it could reach a better performance than the LQR controller in [17]. The PID-based controllers designed in this research has almost similar settling time with the robust controllers and it has noticeably faster response comparing with the LQR controller.

D. Control effort:

Control effort applied to the terminals of DC motors on the UTDTR system is noticeably reduced in closed-loop controlled by PID-based controllers. As high amount of electrical current passes the DC motors in high load, reducing the voltages applied to the terminals causes high level of energy saving which improves one of the most advantages of the UTDTR system prescribed in [6], which is low power consumption.

Detailed information about these controllers is represented in TABLE I. In this table by the term "max" we mean maximum value of the argument in different operating points.

V. CONCLUSION AND FUTURE WORK

In this paper we introduced two PID-based controllers for a tethered Segway, which is a robotic climbing platform with purpose of maneuvering on steep surface. The controllers have been analyzed and their performance have been evaluated regarding to the previously presented methods. The controllers have been simulated on steep surfaces confirming the analytical results. The result shows that the system can stably move on steep surfaces, ranging from 15 degrees to 75 degrees' elevation. Despite of simplicity and low power consumption, the PID-based controllers designed in this research can provide sufficiently good performance for the UTDTR system.

We plan to experimentally implement the proposed controller on the Dome tethered robot described in [6] and test the controller in action. Furthermore, a path planning algorithm would be design to plan the trajectory of the robot from a given point to a desired point on a dome surface.

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