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TID based Control Algorithim for Robot Balancing

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Abstract— **Balancing of Motorized Robots is achieved with a controller tuned for the system to maintain stability. Motorized robot is developed based on the principle of Inverted pendulum various controllers have been implemented and tested. Tilt based control is new control technique its application being in power systems research area. The Tilt based controllers for robotic applications might help in improving overall system performance. But Tilt based controllers are good at attaining stability within a quick period, these characteristics can be taken advantage in robotic applications. Tilted Integral Derivative (TID) and PID Controller is tuned with respect to the mathematical model. The motorized robot is modeled based on inverted pendulum principle. The system response for both controller is analyzed for change in performance, ISA, IAE, ITAE. The controller response is also visualized with a CAD model of the robot in a simulated environment to analyze the performance.**

Keywords—Tilt based controller, Tilt Integral Derivative, Self-Balancing Robot.

I. INTRODUCTION

The Inverted pendulum is an example of Non-Linear system, due to its application in various field and non-linearity. Many researches are done in the Inverted pendulum systems to develop control algorithms with better stability and performances. The system of inverted pendulum in a cart is the principle for self-balancing robots (mono wheel, two Wheel) [3]. The inverted pendulum in a cart can be balanced at a desired angle by moving the cart forward and backward. The velocity is determined by the error angle (the difference between the desired angle and current angle). To maintain the pendulum up straight, the system must analyse the current angle, calculate the required control action to balance the pendulum. In a self-balancing robot, the body of robot acts as inverted pendulum and the motor in the robot is the cart that moves to balance the bot. The mathematical representation of the robot is formed based on the Newton equation of motion. This kind of modelling is named empirical modelling.

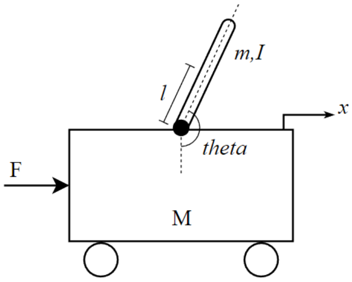

Fig.1 Inverted pendulum model

The Fig.1 represents the inverted pendulum free body model. With mass- M, applied force- F, the distance between centre of gravity of the pendulum and the joint - *l,* displacement -*x,* the mass of the pendulum- m. The control mechanism that calculates the displacement value and direction must respond quickly, highly robust, and simple so that the algorithm can be executed in hardware with less computing power. The controller helps to maintain the robot position irrespective of the environment or external disturbances. Proportional-Integral – Differential (PID) [1], Linear quadratic regulator [1,3], Fuzzy logic, Integral slide mode controller [1] are used for this application.

As discussed in [1], the tilt angle is in vertical axis that makes the system dynamic in nature. The simulation of inverted pendulum system and PID controller is elaborately studied in [5]. As the system is non holonomic and under actuated system it is difficult to attain steady state [10]. Tilted Integral Derivative (TID) belong to the family of fractional order controller, tilted controller has a compensator built in replacing the proportional term in PID. This provides enhanced feedback loop and capable of getting the optimal theoretical response from the system. The design of the TID remains same as PID. The proportional term is replaced by a compensator component called as tilted or tilt. k_t,k_i,k_d are the tilted, integral, derivative constants calculated for the mathematical model derived for the robot.

The TID controller eliminates the error from the system by responding quickly [15]. The TID controller has several advantages over other control systems for self-balancing robots, including its ability to respond quickly to changes in the tilt angle and its robustness to changes in the robot's parameters. The TID controller can also be tuned to optimize the robot's performance, which allows the robot to maintain its balance and stability even in the presence of external disturbances.

II. SYSTEM MODELLING

A. *Inverted pendulum*

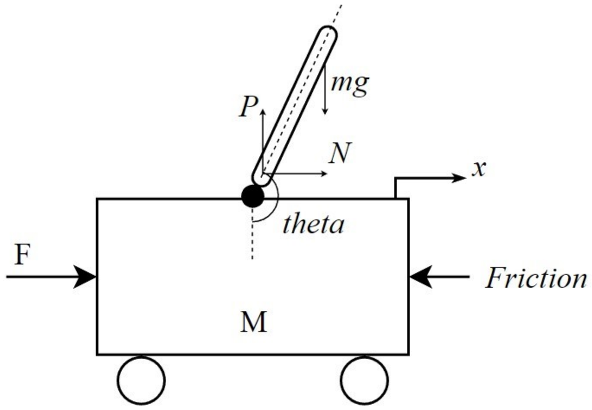

Fig.2 Free body diagram with forces

The model for simulation of the inverted pendulum on cart is derived on the bases of first principal. The equations governing the relationship between cart mass (M), θ - angle between pendulum and cart, friction between the surface and cart ($b\dot{x}$), force applied (F), gravity (mg), force acting on the cart and force acting on the pendulum (N), (P) are detailed below in equations (1) - (4). Free body diagram with all the required parameters and forces are represented in Fig.2.

TABLE I PARAMETERS

Symbols	Quantity	Values
b	Coefficient of friction	0.1 N$m^{-1}s^{-1}$
l	Distance to centre of mass of pendulum	0.4 m
M	Cart mass	0.6 Kg
m	Pendulum mass	0.2 Kg
I	Rotational Inertia	0.006 Kgm^2
g	Gravity	9.81 ms^{-2}

From [4] the equations governing the mathematical model of inverted pendulum are

$$\ddot{x} = \frac{1}{M}(F - N - b\dot{x}) \tag{1}$$

$$\ddot{\theta} = \frac{1}{I}(-Nl\cos\theta - Pl\sin\theta) \tag{2}$$

The relationship between the Horizontal and vertical force N and P are

$$N = m(\ddot{x} - l\dot{\theta}^2\sin\theta + l\ddot{\theta}\cos\theta) \tag{3}$$

$$P = m(l\dot{\theta}^2\cos\theta + l\ddot{\theta}\sin\theta + g) \tag{4}$$

Equations (1), (2), (3), (4) are used to model the inverted pendulum in the Simulink. The modelled block gets force as input and gives cart position and angle of pendulum to cart as output. The equations (1) - (4) has been considered for modelling the pendulum and the same is depicted in Fig.3.

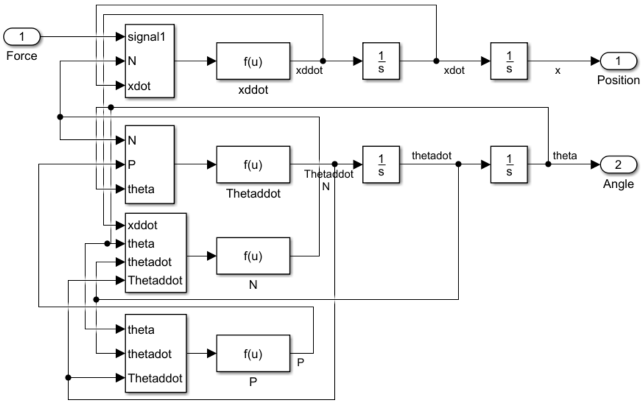

Fig.3 Simulink mathematical model developed

III. CONTROLLER DESIGN

A. *PID Controller*

In the above modelled system, the control variable is the force applied, parameters in interest are the position and angle of cart to pendulum. The closed loop system with PID controller controls the force given to the cart. By varying the force, pendulum is balanced on cart as the cart moves for the force applied. The equation (5) listed below governs the PID controller [2,6].

$$u(t) = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de}{dt} \tag{5}$$

Where PID design parameters are K_p, K_i, K_d and e(t) is the error value. The error value is the deviation of the output to the setpoint of the system [12,16]. The angle of pendulum is fed as feedback to the controller, the set point is set to 0. Assuming that at zero degree the pendulum is perpendicular to the cart. The integral gain overcomes the steady state error introduced by proportional gain, but the system has sustained oscillations. The derivative gain dampens the oscillations introduced by integral gain [11,13].

The PID values are tuned with Ziegler Nichols method, by giving a gain to make the system to have sustained oscillations. The gain value is taken as K_{cr} and the time difference between the two consecutive peaks are taken as P_{cr}.

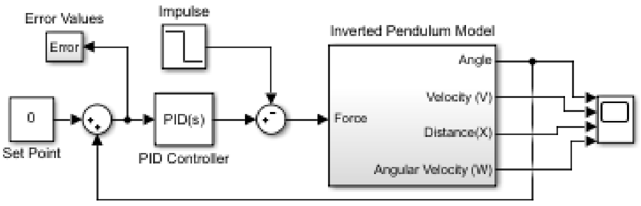

Fig.4 PID controlled inverted pendulum model

Fig.4 is the Simulink model with PID controller and impulse signal added to the force value. The angle is taken as feedback for the controller

TABLE II PID VALUES

PARAMETERS	VALUES
K_p	3
K_i	1.44
K_d	0.361

B. *TID Controller*

The Tilt integral and derivative controller, TID a tunable compensator as given in equation (6). The three parameters are the control boundary and n as the tuning boundary [8]. The PID proportional gain is replaced with tilt component acting as compensator for simpler tuning and better disturbance rejection ratio [9]. The integral component eliminates any systematic error in the robot's control system, and the derivative component adjusts the control effort to dampen any overshoots and stabilize the system.[14]

$$G(s) = \frac{k_t}{s^{(1/n)}} + \frac{k_i}{s} + k_d \cdot s \qquad (6)$$

k_t , k_i , k_d are the tilted, integral, derivative constants calculated for the mathematical model derived for the robot. The TID controller in MATLAB is implemented by using FOMCON toolbox as shown in Fig.5.

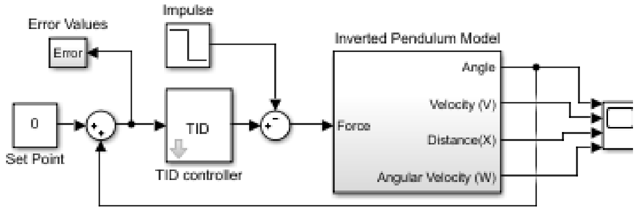

Fig.5 TID controlled inverted pendulum model

TABLE III TID VALUES

PARAMETERS	VALUES
k_t	3
K_i	0.1
K_d	0.1
N	3

IV. RESULTS AND OBSERVATION

The modelled system and controller with the tuned parameters are simulated in Simulink. First the system is tested with PID controller and then with TID controller.

A. *PID Controller Response*

Fig.6 depicts the angle of the system for the impulse input. The time period of the simulation is 100 seconds. The systems settle after a peak overshoot within short time durations.

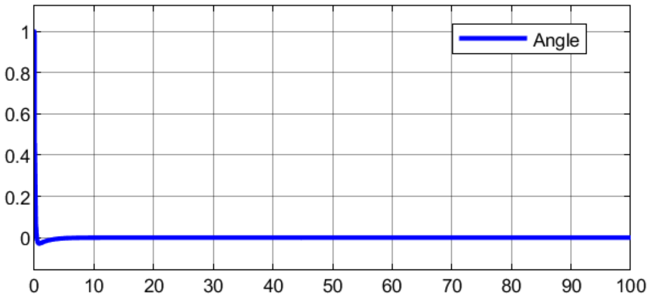

Fig.6 Angle of the system with PID

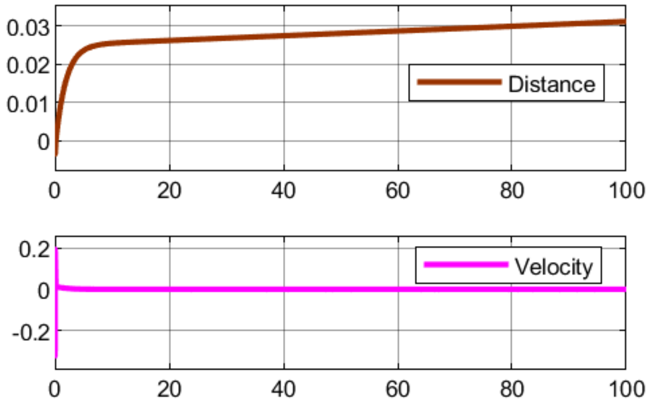

Fig.7 Distance and linear velocity of system with PID

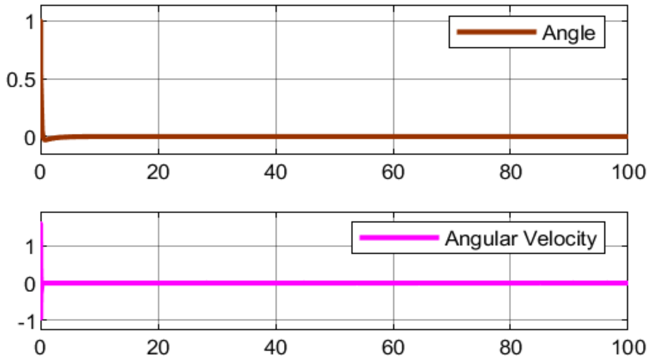

Fig.8 Angle and angular velocity of the system with PID

Linear distance and linear velocity response of the system is shown in Fig 7. The distance is observed to be increasing and the velocity settles down after some oscillations. The Fig.8 represents the (a) angle and (b) angular velocity response of the system. As the angle settles to zero, the angular velocity settles without any further oscillations.

The angular overshoot of the system can still be improved, its observed that the angle response of the PID controller have consecutive overshoots before settling to the set point. TID controller is studied to perform better in elimination of error within a short span of time.

B. *TID Controller Response*

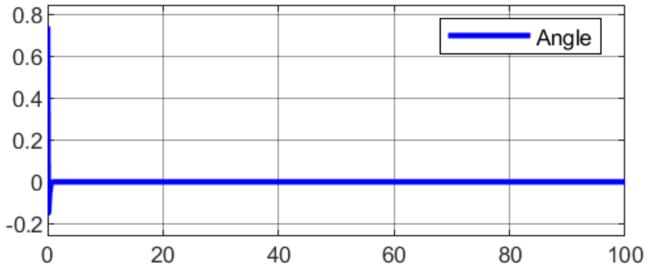

Fig.9 Angle of the system with TID

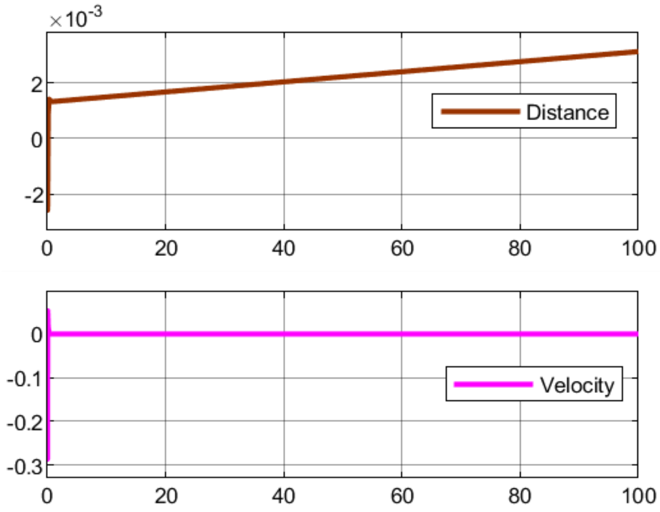

Fig.10 Distance and linear velocity of system with TID

The Fig.9 is the angle output of the system for the impulse input. The time of the simulation is 100 seconds. The overshoot is observed at the time of the impulse signal and a undershoot occurs to settle down to zero. The Fig.10 is the linear distance and linear velocity of the system with TID controller. The distance traveled by the cart keeps increasing as time progresses.

The errors from systems with PID and TID controller is compared to determine the performance difference between the controllers. The error criteria considered are IAE, ISE, ITAE [7].

In IAE the performance index is calculated using the equation (7)

$$IAE = \int_0^{\infty} |e(t)|\, dt \tag{7}$$

In ISE the performance index is calculated using the equation (8)

$$ISE = \int_0^{\infty} e^2(t) dt \tag{8}$$

For ITAE the performance index is calculated using equation (9)

$$ITAE = \int_0^{\infty} t\ |e(t)|\ dt \tag{9}$$

TABLE IV ERROR VALUES

Error	IAE	ISE	ITAE
PID	0.13	0.02824	0.1578
TID	0.06712	0.02099	0.009849

The Fig.11 is the angle and angular velocity of system with TID controller. The system settles after an overshoot and undershoot. The ISA, IAE, ITAE of the systems with PID and TID controller are tabulated in Table IV. The TID controller has less values for all the errors listed. The number of peak overshoots are the number of oscillation that robot makes before attaining stable postion as depicted in Fig.12.

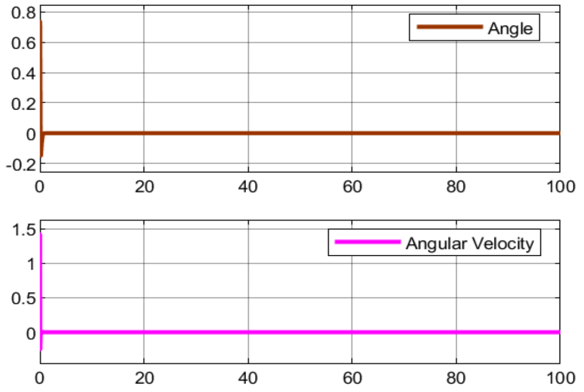

Fig.11 Angle and angular velocity of the system with TID

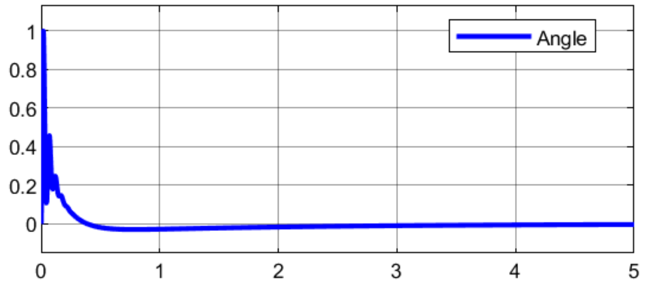

Fig.12 Angle response of system with PID for time period of 5 seconds

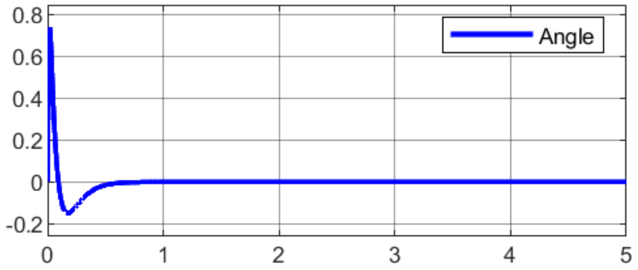

Fig.13 Angle response of system with TID for time period of 5 seconds

As observed from the Fig.13 the TID controller helps the robot to attain stability within a short period and with less overshoot. This control strategy is better in responding to the external envinroment to make robust control actions.

TABLE V OVERSHOOT AND UNDERSHOOT VALUES

Controller	PID	TID
Overshoot	0.9997	0.7359
Undershoot	-0.0289	-0.1485

Fig.12 is the angle of pendulum to cart with PID controller. Its observed that the angle reponse for the system undergoes some oscillations that decays after a peak over shoot and the response is settled to zero. The Fig.13 is the angle response of the system with TID controller. Its observed that the angle reponse for the system has a peak overshoot the system settles down without further oscillations after a undershoot. The position response for both the controller keeps increasing with time. This impiles the cart keeps on moving to maintain the angle between the cart and pendulum.

V. CONCLUSION

The system is modelled using basic principle modeling and performance of the PID and TID are observed. The TID reponse is better with good error values compared to the system respone with PID and its error values. Drawback of tranfer function modeling with basic principles is the non linearity of the objective and limts the model to control only one variable and thus in this case the distance keeps increaseing without any restriction. It is prefered to use state space modeling or other multi output systems to have a bettter control over the varibles.

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