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Novel Cross-Coupling Motion Control for Motion Controller for Social Robotics

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Abstract: - A social robot is an autonomous mobile robot that interacts and communicates with humans following the social rules attached to its role. Two-wheel autonomous mobile robot that capable of interactive, communicative behaviour is considered social in this research. Current mobile robot motion accuracy has not been yet achieved to full satisfaction. This paper presents a novel technique of Cross-Coupling Motion Control for Motion Controller, (NC-CMCMC), for Two-Wheel Mobile Robot to achieve higher motion accuracy. Previous Cross-Coupling control techniques are based on the consideration of only internal disturbances. The technique presented in this paper is based on the consideration of both internal and external disturbances simultaneously. Similarly, previous Cross-Coupling control techniques used only feed-back signals to correct the errors of the system. NC-CMCMC has employed feed-back and feed-forward signals at the same time to achieve more accurate results. NC-CMCMC has been mathematically modelled and simulated by using MATLAB-SIMULINK. Achieved results show that the suggested technique is robust and yield zero transient response and zero steady state errors. Hence, NC-CMCMC will yield zero position and orientation errors which will keep the mobile robot on the same trajectory path (either straight or curve) despite continuous internal and external disturbances that affect either of motors.

Key-Words: - Cross-Coupling motion control, BLDC Motor, Mobile robot, Social robot.

1 Introduction

There are quite few applications that need cross-coupling controller to have more accuracy in their operations. Two-Wheel mobile robots that act as social robots are one example that needs cross-coupling control to achieve satisfactory accuracy in their trajectory [1] [2] [3].

As mentioned before, social robot is an autonomous mobile robot that interacts and communicates with humans following the social rules attached to its role or it is a robot that can behave like humans [4] [5]. There are many features of the social rules and behaviours in human society, such as: passing and following each other in corridor, going through door out and in, using elevators, standing and waiting in line, dancing … etc [4]. In this paper, two-wheel mobile robot is considered as a social behavioural robot that interacts and communicates with people and behaves more like them. From the aforementioned, two-wheel mobile social robot needs high accuracy in its motion system to interact and communicate with humans effectively. Mobile robot motion system controls the wheels and provides translation, rotation and movement of the mobile robot [4].

Two-wheel mobile robots are driven by two independently controlled motors; with lack of full coordination [1] [6] [7]. To solve the coordination problem between the two-wheel control loops, a cross-coupling controller was introduced in [1] [6]. The cross-coupling controllers introduced in [1] [6], were based on the consideration of the internal disturbances and used the feedback signals to correct system errors. Those types of cross-coupling controllers are good to guarantee zero steady-state errors [1] [6].

However, despite the aforementioned, lack of accuracy in trajectory of mobile robots still occurs. Lack of accuracy in trajectory of mobile robots is due to external and internal disturbances that affect each control loop. Therefore, to improve the accuracy in the mobile robot trajectory, *external* and *internal* disturbances must be considered in order to achieve zero transient response and zero steady state errors in the system output response, which will lead to satisfactory accuracy in mobile robot motion.

This paper deals with new suggested motion control technique to improve the accuracy in mobile social robot resultant trajectory to interact and communicate with humans successfully. This technique is based on considering both internal and external disturbances that affect each control loop by employing feed-back and feed-forward signals at the same time to correct system errors.

It is known that disturbances that affect one control loop may differ from disturbances that affect the other loop [1]. This difference will lead to none-zero transient response and none-zero steady state errors. Thus, to eliminate these errors and to improve the accuracy in the whole system, this difference must be considered and shared between both control loops, as it will be shown in this paper.

This paper is composed of six sections. Section 2, shows the mobile robot motion control errors that occur due to disturbances effect. Sections 3 and 4, show and discuss the suggested technique of Cross coupling and show how the suggested idea will improve the accuracy and the motion control performance of the system. Also, section 4, shows the mathematical analyses of the system and the suggested Crosscoupling technique. In section 5, simulation results are presented. Conclusion is provided in section 6.

2 Mobile Robot Motion Control Disturbance Errors

External and Internal disturbances that affect the motion system of the mobile robot cause errors in the motion control system and reflected on the transient and steady state responses. The type of errors depends on so many conditions:

a- Type of disturbances: either External or Internal.

b- Type of robot trajectory: either Curve or Straight.

Disturbances that affect a motion control system divided into external and internal which cause external and internal errors [1] [8]. External errors are caused by external disturbances, which may appear while the robot executes its task and interacts with the surrounding environment. For example, any external force affect the system will cause those errors. As a result, the robot may go out of its required path.

Internal errors are caused by internal disturbances, which affect the wheel motion behaviour and consequently the system accuracy. For various reasons, internal disturbances are caused and occurred on the robot motors and wheels. The main sources for these disturbances are:

a- Torque internal disturbances, which affect the motor because of the changing in motor flux, rotor position, payload…etc [8].

b- Moving in a curve or nonlinear path.

c- Different drive loop parameters and different disturbances acting on each loop which affect the transient and steady state responses [1] [6].

When the robot moves in a direct line, disturbances may cause an errors like tracking error (e_t) which is the distance between the actual and desired position in the direction of travel, and orientation tracking error (e_θ) which is the displacement about the desired path in angle (θ) as shown in Fig.1 below.

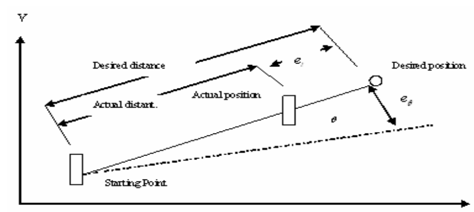


Fig.1 Direct Line Motion Error

In this case, the robot velocity is refers to the mid point of the vehicle and it can be defined as: [7]

$$V = \frac{V_L + V_R}{2}$$

Where V is the robot speed, V_L is the left wheel speed and V_R is the right wheel speed.

This velocity can be defined as a term of changing the moving distance of the robot per time unites as:

$$V = \frac{ds}{dt}$$

Where: ***s*** is the changing in the moving distance of the robot. Also, when it moves in a curve or nonlinear path, disturbances may cause another types of errors: [1]

a- Contouring errors (e_c): Which is the perpendicular distance between the actual contouring path and the desired one as shown in Fig.2 below.

b- Orientation error (e_θ): which is the error in the direction angle or the angular displacement about the actual curve path as shown in Fig.2 below.

c- Tracking error (e_t): which is the distance between the actual and desired position in the direction of travel as shown in Fig.2 below.

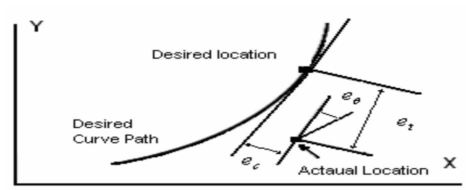


Fig.2 Curve Line Motion Errors.

In this case robot linear and angular velocities are: [1] [9]

$$V_X = \frac{V_L + V_R}{2} Sin\theta$$

$$V_Y = \frac{V_L + V_R}{2} Cos\theta$$

$$V_\theta = \frac{V_L - V_R}{d}$$

Where X, Y are the position of the robot in the coordinate system, θ is the orientation angle, V_X, V_Y are the robot velocity in X and Y directions, V_θ is the angular velocity of the robot, V_L is the left wheel speed and V_R is the right wheel speed and d is the distance between the two drive wheels.

From the aforementioned, the speed of the two wheels will determine the speed and orientation of the mobile robot for all directions. This can be summarized as: [7]

When $V_L > V_R$ the vehicle moves toward the right.

When $V_L = V_R$ the vehicle moves straight.

When $V_L < V_R$ the vehicle moves toward the left.

When $V_L + V_R$=0 the vehicle is making Zero Turn Radius (ZTR).

In order to control the robot velocity and position despite of continuous disturbances with high accuracy the following cross coupling control technique is suggested and analysed.

3 Suggested New Cross-coupling Control Technique

The suggested technique is a Novel Cross-Coupling Motion Control for Motion Controller, **(NC-CMCMC),** for Two-Wheel Mobile Social Robot. This technique is suggested to improve the accuracy in the mobile social robot resultant to achieve zero transient response and zero steady state errors.

This technique is based on the consideration of disturbances that affect each control loop either external or internal. It is known that disturbances that affect one control loop may differ than those affect the other loop. This difference will lead to none zero transient response and none zero steady state errors. Thus, to eliminate these errors and to improve the accuracy in the whole system, this difference must be considered and shared between both control loops as shown in the system block diagram, Fig.4. As shown in Fig.4 below, the motion system of the mobile robot is composed of two-motor control loops. Coordinating both loops with each other using the suggested cross-coupling technique, controls the whole motion system of the mobile social robot.

In this technique, disturbance errors are considered and distributed between booth loops at the same time by employing feed-back and feed-forward signals as an input for the cross-coupling controller as shown in Fig.4. PI controller is used to control the resultant error signal. The correction signal from the output of the PI controller is fed again to the input of each control loop to keep them Coordinated, synchronised and balanced at any time.

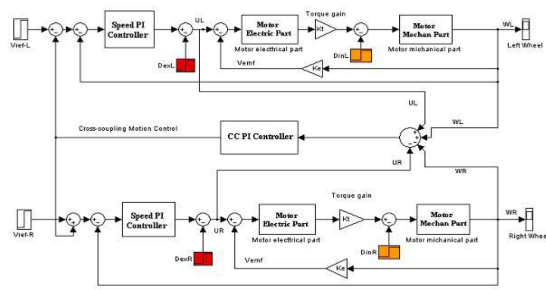


Fig.4 System Block Diagram

As shown in Fig.4 above, two expected errors are related between both loops to improve the system accuracy and obtain zero transient response and zero steady state errors. These two expected errors are:

a- Disturbance error ($e_{dist.}$) is the difference between motors input signals that may be affected by external disturbances that affect each control loop. This difference must be considered and it is obtained from feed-forward signals, as:

$$e_{dist} = U_L - U_R$$

b- Output error (e_{out}) is the difference between motors output signals that may be affected by internal and external disturbances that affect each control loop. This difference must be considered and it is obtained from feedback signals, as:

$$e_{outt} = W_L - W_R$$

As a result and by implementing the suggested technique following features are expected:

a- Zero transient response and Zero steady state errors.

b- Keeping the system coordinated, synchronised and balanced at any given time.

c- Improving the accuracy in the robot trajectory tracking in spite of continuous disturbances that affect the control system, from either external or internal sources.

The whole system with the suggested technique is fully analysed in the following section.

4 Motion Control System Analyses and Algorithm

The considered control system composed of two-motor control loops with the new suggested cross-coupling control to couple and coordinate between them. Each motor control loop has its own PI controllers. The cross coupling control has dual feedback and feed-forward signals with comparator and PI controller as has been shown in Fig.4 before. All control modules are performed and modelled in discrete domain as shown in the following sub-sections.

4.1 BLDC Motor Speed Model

Three-phase permanent magnet brushless DC motor (BLDC) is considered. BLDC motors have a widely use in control systems. They can directly provide rotary and transitional motion. Also, they can easily couple with wheels or drums. BLDC motor consists of two parts, electrical part and mechanical part like any DC motor. The 3-phase electric circuit and free body diagram of the BLDC motor are shown in Fig.5 below [10] [11] [12] [13].

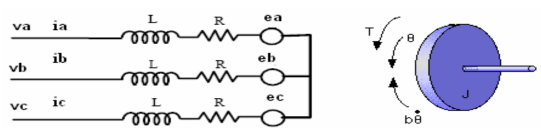


Fig.5 BLDC Motor 3-phase electric circuit & Free-Body diagram

From the circuit above, the voltage equations of 3-phase with six switches and Y connected motor can be expressed as:

$$\begin{vmatrix} v_a \\ v_b \\ v_c \end{vmatrix} = \begin{vmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{vmatrix} . \begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix} + \begin{vmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{vmatrix} . \frac{d}{dt} \begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix} + \begin{vmatrix} e_a \\ e_b \\ e_c \end{vmatrix}$$

Where v_a, v_b & v_c are 3-phase voltages, R the phase resistance, L the phase inductance, i_a, i_b & i_c are phase currents, e_a, e_b & e_c are phase back emf.

However, in this kind of motor, only two of three phases are conducting simultaneously and at any time. Therefore, the equivalent electrical circuit for BLDC motor modelling is as shown below.

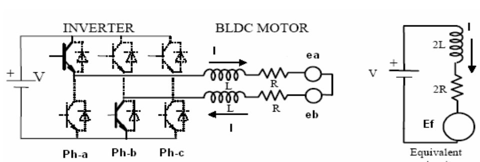


Fig.6 BLDC Motor equivalent circuit when only 2-pheses conducting

From the circuit shown in Fig.6, motor terminal voltage based on Kirchoff's low is performed as:

$$V = 2R.I + 2L\frac{dI}{dt} + E_f$$
$$V - E_f = 2R.I + 2L\frac{dI}{dt} \qquad (1)$$

Where V is the supply voltage of the inverter, R & L are the winding resistance and inductance respectively, I is the phase armature current being controlled by PWM, and E_f is the back emf voltage between conducting phases. Back emf voltage can be expressed as a function of rotor speed as below.

$$E_f = K_e.\dot{\theta}$$

Where: K_e is the motor constant and $\dot{\theta}$ is the rotor angular velocity. By substituting E_f in the differential equation (1), it becomes:

$$V - K_e.\dot{\theta} = 2R.I + 2L\frac{dI}{dt} \qquad (2)$$

From the free body diagram the mechanical part equation is performed based on Newton law.

$$\sum T = J.\alpha$$

Where T is the motor torque, J is the rotor inertia and $\alpha = \ddot{\theta}$ is the rotor acceleration. The motor torque is related to the armature current I by torque constant K_t. It looks like as:

$$T = K_t.I$$

Referring to the motor free body diagram and Newton's law, then:

$$T = J.\ddot{\theta} + b.\dot{\theta}$$
$$K_t.I = J.\ddot{\theta} + b.\dot{\theta} \qquad (3)$$

Where b is the damping ratio of the mechanical system, $\ddot{\theta}$ is the rotor acceleration, $\dot{\theta}$ is the rotor angular velocity and θ is the rotor angular position. Considering $K_t = K_e = K$ is the motor constant.

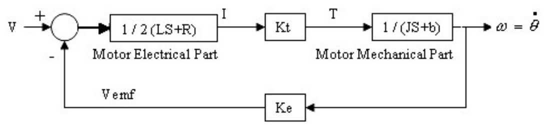
From equations (2) and (3) the motor speed transfer function can be performed. Using Laplace transforms, the differential equations (2) and (3) can be expressed in terms of S.

$$V - KS\theta(s) = 2(R + LS)I(s) \qquad (4)$$
$$(JS + b)S\theta(s) = KI(s) \qquad (5)$$

By solving the above equations (4) and (5) the following motor transfer function is obtained, where the rotating speed ($\dot{\theta} = \omega$) is the output and the voltage (V) is the input.

$$\frac{\dot{\theta}}{V} = \frac{S\theta(s)}{V} = \frac{K}{2(R+LS)(b+JS)+K^2} \qquad (6)$$

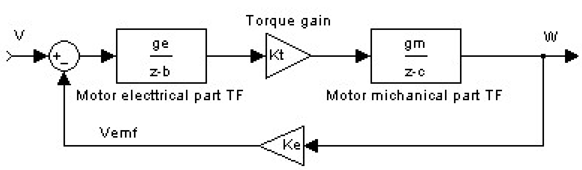
The BLDC Motor electrical and mechanical parts model in S domain is drawn below:



To design a digital system the continuous transfer function needs to be converted to discrete transfer function (from S domain to Z domain). Using MATLAB and 'Zoh' method the above transfer function, equation (6), can be converted to discrete transfer function after substituting motor constant values. In general, after the conversion, it can take the poles-zeroes form in Z domain as:

$$\frac{\omega(z)}{V(z)} = \frac{g(Z+a)}{(Z-b)(Z-c)} \qquad (7)$$

Where g is the model gain, a is the model zero and b & c are model poles. The BLDC Motor electrical and mechanical parts model in Z domain is drawn below.



4.2 Novel Cross-Coupling Control System Analyses and Algorithm

In this section, the mathematical description of the suggested technique is performed and discussed. Since external and internal disturbances that affect two independent motors are considered to improve the accuracy in the robot resultant path, the suggested cross-coupling control technique shown in Fig.7 below is studied and analysed.

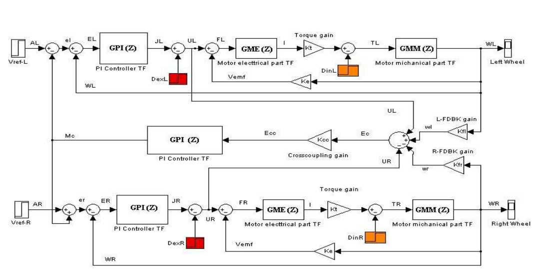


Fig.7 System mathematical components with External & Internal Disturbance parameters.

By analysing the system in Fig.7, then:

$$J_L = E_L.G_{PI}(Z) = [A_L - M_C - W_L].G_{PI}(Z) \qquad (8)$$

Where A_L is the reference input to the left control loop, M_C is the digital cross-coupling correction signal fed to both loops, W_L is the left loop output speed, E_L is the tracking error signal sent to the PI controller input, J_L is the output of the PI controller signal and $G_{PI}(Z)$ is the PI controller discrete TF which looks like:

$$\frac{J(z)}{E(z)} = \frac{g(z-a)}{(z-b)}$$

After exertion the effect of external and internal disturbances, as shown in Fig.7, following formulas can be obtained:

$$U_L = J_L - D_{exL} \qquad (9)$$
$$F_L = U_L - K_e.W_L$$

Where D_{exL} is the external disturbance affecting the left loop, U_L is the motor input effected signal, K_e is the motor constant and W_L is the left control loop output speed. The output of the left loop can be expressed as:

$$W_L = F_L.K_t.G_{ME}(Z).G_{MM}(Z) - D_{inL}.G_{MM}(Z) \qquad (10)$$

Where K_t is the torque constant, $G_{ME}(Z)$ is motor electrical part discrete TF; $G_{MM}(Z)$ is motor mechanical part discrete TF and D_{inL} is the internal disturbance affecting the left loop.

By substituting previous equations (8), (9) and (10) in each other, the following output equation for the left loop is obtained:

$$W_L = \frac{K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).[A_L - M_C] - K_t.D_{exL}.G_{ME}.G_{MM} - D_{inL}.G_{MM}(Z)}{1 + K_t.G_{ME}(Z).G_{MM}(Z)[G_{PI}(Z) + K_e K_t]} \qquad (11)$$

Following the same procedure before, the output speed signal of the right loop can be obtained which looks like:

$$W_R = \frac{K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).[A_R + M_C] - K_t.D_{exR}.G_{ME}.G_{MM} - D_{inR}.G_{MM}(Z)}{1 + K_t.G_{ME}(Z).G_{MM}(Z)[G_{PI}(Z) + K_e K_t]} \qquad (12)$$

Where A_R is the reference input of the right control loop, D_{exR} is the external disturbance affecting the right loop and D_{inR} is the internal disturbance affecting the right loop.

To see the effect of the suggested cross-coupling technique on the system, the output signal of the cross-coupling technique (M_C) must be found. The output cross-coupling correction signal can be found as the following:

$$E_C = (w_l - w_r) + (U_L - U_R)$$
$$w_l = K_{fl}.W_L$$
$$w_r = K_{fr}.W_R$$
$$E_{CC} = K_{CC}.E_C$$

Where E_C, the crosscoupling error signal, is obtained from the difference between the dual feed signals, K_{fl} is the left loop feedback gain and K_{fr} is the right loop feedback gain. These two gains (K_{fl} & K_{fr}) are introduced to allow the robot to move in curved paths. If the robot moves in straight line, then both gains will be set to one, $K_{fl} = K_{fr} = 1$.

However, if the robot moves in curved path, the centre of the robot must move along a circle of radius R. In this case these two gains can be expressed as:

$$K_{fl} = 1 \quad \text{and} \quad K_{fr} = \frac{1 - d/2R}{1 + d/2R}$$

Where d is the distance between the two wheels and R is the radius of the curved path. The gain K_{CC} is the cross-coupling gain. This gain can be adjusted to obtain a zero difference between the transient responses of both loops in case of continuous disturbances.

Now, the output of the suggested crosscoupling control technique is:

$$M_C = E_{CC}.G_{PI}(Z)$$

Where E_{CC} is the cross-coupling PI controller input signal and $G_{PI}(Z)$ is the PI controller discrete TF.

By substituting M_C in equations (11) and (12), final equations of both control loops using the suggested cross-coupling technique can be found. The final two output equations of left and right control loop look like:

$$W_L = \frac{K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).\left[A_L - M_C\right] - K_t.D_{exL}.G_{ME}.G_{MM} - D_{inL}.G_{MM}(Z)}{1 + K_t.G_{ME}(Z).G_{MM}(Z)\left[G_{PI}(Z) + K_e K_t\right]}$$

$$= \frac{K_{cc}.K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).G_{PIcc}(Z).\left[K_{fr}W_R + \left(U_R - U_L\right)\right] + G_{MM}(Z).\left[A_L.K_t.G_{ME}(Z).G_{PI}(Z) - K_t.D_{exL}.G_{ME} - D_{inL}\right]}{1 + K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z) + K_{cc}.K_t.K_{fl}.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).G_{PIcc}(Z) + K_e.K_t.G_{ME}(Z).G_{MM}(Z)}$$

$$= \frac{K_{cc}.K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).G_{PIcc}(Z).\left[K_{fr}W_R + \left(J_R - J_L\right) + \left(D_{exL} - D_{exR}\right)\right] + G_{MM}(Z).\left[A_L.K_t.G_{ME}(Z).G_{PI}(Z) - K_t.D_{exL}.G_{ME} - D_{inL}\right]}{1 + K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z) + K_{cc}.K_t.K_{fl}.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).G_{PIcc}(Z) + K_e.K_t.G_{ME}(Z).G_{MM}(Z)}$$

$$W_R = \frac{K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).\left[A_R + M_C\right] - K_t.D_{exR}.G_{ME}.G_{MM} - D_{inR}.G_{MM}(Z)}{1 + K_t.G_{ME}(Z).G_{MM}(Z)\left[G_{PI}(Z) + K_e K_t\right]}$$

$$= \frac{K_{cc}.K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).G_{PIcc}(Z).\left[K_{fl}W_L + \left(U_L - U_R\right)\right] + G_{MM}(Z).\left[A_R.K_t.G_{ME}(Z).G_{PI}(Z) - K_t.D_{exR}.G_{ME} - D_{inR}\right]}{1 + K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z) - K_{cc}.K_t.K_{fr}.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).G_{PIcc}(Z) + K_e.K_t.G_{ME}(Z).G_{MM}(Z)}$$

$$= \frac{K_{cc}.K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).G_{PIcc}(Z).\left[K_{fl}W_L + \left(J_L - J_R\right) + \left(D_{exR} - D_{exL}\right)\right] + G_{MM}(Z).\left[A_R.K_t.G_{ME}(Z).G_{PI}(Z) - K_t.D_{exR}.G_{ME} - D_{inR}\right]}{1 + K_t.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z) - K_{cc}.K_t.K_{fr}.G_{PI}(Z).G_{ME}(Z).G_{MM}(Z).G_{PIcc}(Z) + K_e.K_t.G_{ME}(Z).G_{MM}(Z)}$$

From output equations, disturbances ***(external: D_{exL} & D_{exR})*** and ***(internal: D_{inL} & D_{inR})*** are considered. The difference between both loop command, **±(J_L-J_R)**, and disturbance, **±(D_{exL}-D_{exR})**, signals are coordinated between both motor control loops. Also, equations show that, internal disturbances affect the motor mechanical part and external disturbances affect both electrical and mechanical parts. Moreover, the output of each loop is shared and computed in the other output loop, **(W_L&W_R)**. Both equations illustrate that the suggested technique is robust, stable and reject continuous disturbances *(external* and *internal)* that affect either control loops or both of them.

5 Simulation Results

The complete system with the suggested cross-coupling technique shown in Fig.7 is modelled and simulated using MATLAB-SIMULINK. Simulation results of the system speed outputs are obtained successfully as the following:

a- Firstly, the system is simulated without any disturbances affect the system. A step reference input signal is applied to the input of each control loop as shown in Fig.7 with zero external and internal disturbances. The speed output response of the system for both control loops is obtained as shown in Fig.8 below.

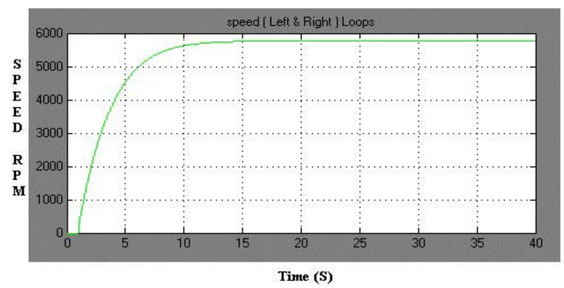


Fig.8 Both loop speed output response together, when Disturbances = 0

Fig.8 shows that the system has zero transient response and zero steady state errors in the case of no disturbances affect the system. Also, it shows that the system speed output is reached up to 5800 RPM.

b- The system is simulated when both control loops encounter external and internal disturbances at the same time, at time=0s. Simulation result is obtained for both control loops together as shown in Fig.9.

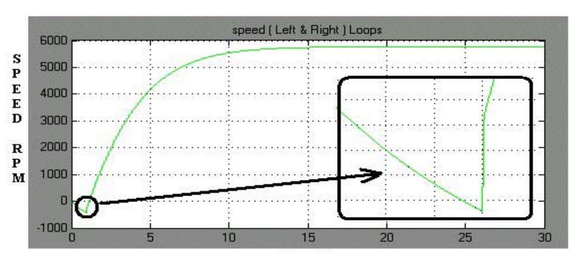


Fig.9 System speed output response when external and internal disturbances affected both loops at t= 0s

Fig.9 shows, how the robustness of the suggested technique is. It shows that the system has zero transient response and zero steady state errors despite continuous external and internal disturbances that affect each motor control loop. That means, the new cross-coupling control technique coordinates and synchronises between both control loops as expected and obtained from system speed output equations before. From the zooming at time=0s, the suggested technique guarantees a zero steady state error and zero deference between the transient responses of both loops.

c- For more investigation the system simulated when both control loops are encountered different disturbances at time=20s. Different external and internal disturbances affect both loops with the new suggested cross-coupling. Simulation result is obtained as shown in Fig.10 below. From the zooming at time=20s, the suggested technique guarantees zero steady state and zero transient errors even with continuous external and internal disturbances that affect each motor control loop.

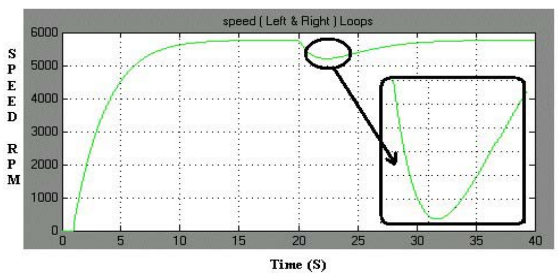
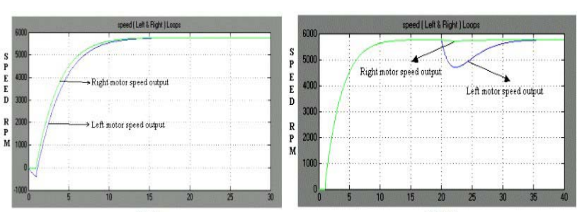


Fig.10 System speed output response when external and internal disturbances affected both loops at the same time at t = 20 s

d-To illustrate and prove the robustness of the suggested technique and to illustrate its accuracy, the system is simulated without considering the suggested cross-coupling control idea. By repeating steps **b** and **c** without considering the suggested cross-coupling control idea, simulation results are obtained as shown in Fig.11.

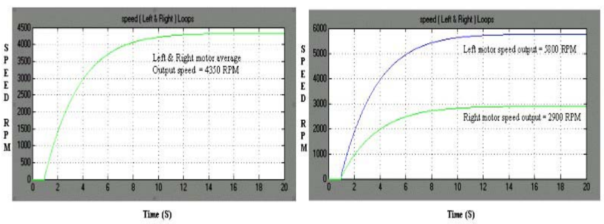


(a) (b)

Fig.11 System speed output response when both loops are encountered different disturbances without considering the suggested technique,
(a): at t = 0 s & (b) at t = 10 s

Without considering the new technique an error appears between both loops transient responses as shown in Fig.11. This will affect the robot resultant path accuracy. Fig.10 and Fig.11 show that the suggested technique is robust and accurate.

e- To illustrate the effect of the system inputs to its outputs, the system simulated with tow different input set points. Simulation results obtained as shown in Fig.12 below. From Fig.12, the output of the system using the suggested cross-coupling idea is equal to the formula: $V = \frac{V_L + V_R}{2}$



(a) (b)

Fig.12 System speed output response with two different input set points
(a) With the suggested crosscoupling technique.
(b) Without the suggested crosscoupling technique.

f- As mentioned before the suggested cross-coupling technique is designed by tacking in consideration the movement of the social mobile robot in straight line and curved line by introducing two gains ***(K_{fl} & K_{fr})*** as shown in Fig.7 before. If these two gains are equal that mains the system will move in straight line otherwise the system will move in curved line according to the following equation.

$$K_{fl} = 1 \quad \text{and} \quad K_{fr} = \frac{1 - d/2R}{1 + d/2R}$$

Where d is the distance between the two wheels and R is the radius of the curved path. To improve that, the system simulated to move in a curve path that has a radius $R = 1$ *meter* and the distance between the two wheels $d=0.3$ *meter*. Fig.13 below shows that the speed of the right motor is faster than the left motor. That mains, the mobile robot moves in a curved path with R =*1 meter* to the left.

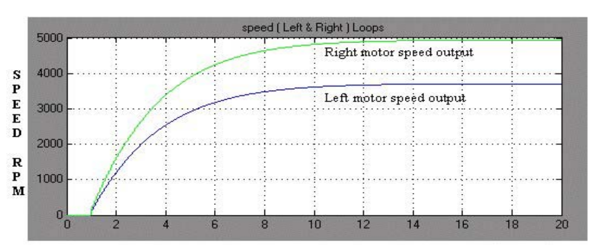


Fig.13 System moves in a curved path

From simulation results, it can be seen that the system has zero transient response and zero steady state errors with considering the suggested cross-coupling technique. Also they show that the system is robust, stable and rejects continuous external and internal disturbances as expected and obtained from system mathematical output equations in section (4.2). Also, the suggested technique has the ability to let the system moves in straight and curved paths to all directions.

6 Conclusion

Novel Cross-Coupling Motion Control for Motion Controller **(NC-CMCMC),** for Two-Wheel Mobile Social Robot is analysed and modelled. A mathematical model for the proposed technique has been developed. The system is simulated using MATLAB-SIMULIK. Simulation results have been achieved and presented. Simulation results show that the suggested technique is robust and guarantee zero steady state error and zero transient response error in spite of continuous external and internal disturbances that affect both control loops. The suggested technique is expected to improve the accuracy in the mobile robot resultant path despite of the continuous disturbances that affect the system from either external or internal sources.

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