An Intelligent Robust Control of Wheeled Mobile Robot in Restricted Environment

MOHAMMED A. H. ALI[1, a], MUSA MAILAH[2], WAN AZHAR B. YUSSOF[1], ZAMZURI BIN HAMEDON[1], ZULKILI B. M. YUSSOF[1]

[1]Faculty of Manufacturing Engineering, Universiti Malaysia Pahang
26600 Pekan, Pahang
MALAYSIA

[2]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia
81310 Skudai, Johor B
MALAYSIA

[a]moh.ali.hashim@gmail.com

Abstract— This paper presents a simulation study of hybrid control strategy to control the motion of wheeled mobile robot (WMR) in the restricted environment. The implementation of the robot path planning in restricted environments needs a suitable robust controller to avoid known/unknown disturbances and guarantee zero track errors. A proportional derivative active force control (PDAFC) scheme is incorporated with artificial intelligent techniques, namely, fuzzy logic (FL) to effectively estimate the actual torque applied on the robot wheels. Several kinds of trajectories in the restricted environment with unexpected changes in their trajectory has been used to test the proposed control system. The simulation study was carried out using software interface (MATLAB / SIMULINK). The results demonstrate a better performance and higher capability of PDAFC controller for disturbance rejection in comparison with PD and AFC controllers.

Keywords— Wheeled Mobile Robot; Active Force Controller; PD Controller; Restricted Environment

1 Introduction

The control of mobile robot in restricted environments such as in roads and factories areas , during the path execution, still a complicated problem in robot researches. This is due to that in such area, the robot needs to maintain perminantly the track errors at zero level and the WMR robot must follow robustly the pre-defined path using a suitable control system; otherwise it can cause to crash other objects.

Active Force Control scheme is one of the most useful controller that can eliminate the tracking error very well. A well-functioning Active Force Controller can compare the actual value with ideal value that coming from applied torque and acceleration sensor parameter. There are always an external and inner loops in Active Force Controller. External loop usually functions as kinematic system and contain traditional controller like PD controller. The inner loop always functions as dynamic system and contains the Active Force Controller strategy.

Active Force Controller is firstly introduced to control the dynamic of a robotic arm and gripper [1]. The accelerometer and torque sensors are used to estimate the difference between the applied and actual torques.

Proportional-Integral combined with Active Force Control (PIAFC) algorithm has been used to recompense the dynamic behaviour of the robotic system which can't only delete the known disturbances but also unknown disturbances [2]. The effectiveness as well as robustness of the control scheme in this work can be observed only if the control schemes use active force control.

An active force control schemes has been applied on the 5-links biped robot [3]. This control system presents robustness and stability behaviour even in presence of the disturbances as AFC scheme is succeeded to compensate external disturbances acting on the biped system. The quadratic cost function of tracking errors are also minimized by predictive controller based AFC.

Active Force Control (AFC) with Fuzzy Logic (AFCAFL) controller has been applied on a robotic arm that are moving by Pneumatic Artificial Muscle [4]. The study uses fuzzy logic (FL) technique to find the optimized value of the inertia matrix in the robotic arm control system. AFCPID mechanisms also play an important role to make system more effective and robustness.

Active Force Control (AFC) has been utilized to reduce friction-induced vibration [5]. The AFC based control strategy reduces the unwanted effects of the vibration source so that Friction Induced Vibration (FIV) can be decreased. Besides that, AFC based scheme also can increase the robustness of the system and reduce the vibrations of FIV system.

An Active Force Control for operating a mobile robot with 4 wheels together with kinematic controller based algorithm is used to solve both tracking and regulation problems [6]. Tunable oscillator produces some reformed states to track some expected or unexpected signals.

Hybrid Resolved Acceleration Control (RAC)-with AFC controller is used to control robot in a pre-planned path during passing through complicated environments [7]. The Comparison between Resolved Acceleration Control and Active Force Control has been done to test the controller capability in reducing tracking errors. The controller maintain the mobile robot on its path by tracking it on the pre-defined path with capability to eliminate the effect of the disturbances.

Implementation of evolutionary AFC strategy in 5-link biped robot has made the system robust and stable even-though under effect of disturbances or obstacles [8]. AFCCA scheme is giving the excellent trajectory tracking performance and AFC scheme demonstrates high accuracy and robustness in the biped-tracking problem.

Tracking performance on mobile manipulator controller based on Active Force Controller was proposed to eliminate all effect of any disturbances that exist in the system [9]. The AFC scheme demonstrates a better noise rejection and faster in computational time in comparison with the computed torque controller.

Active Force Control with Nonlinear Predictive Control has been introduced to enhance the trajectory tracking and increase the robustness against various types of known and unknown uncertainties for Five-Link Biped Model [10]. Results show that the Nonlinear Predictive Control with Active Force Control (NPC-AFC) is more accurate and it has small tracking errors in comparison to average tracking errors of Nonlinear Predictive Control (NPC).

In this paper, we will develop a PD-AFC control scheme to control the robot in the restricted environments. Several types of trajectories will be used to test the proposed control algorithm. The comparison between PD, AFC and PD-AFC will be presented with/without presence of disturbances to show the stability and robustness of control system.

2 Modeling of Wheeled Mobile Robot

The proposed Wheeled Mobile Robot comprises three wheels driving system with two differential drive and one castor wheel as depicted in Fig. 1. The motion of the Wheeled Mobile Robot can be described in global and local coordinate system as shown in Fig. 1.

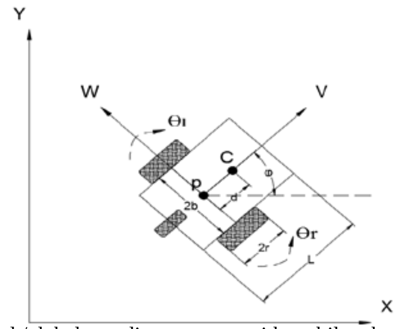


Fig. 1: Local /global coordinate system with mobile robot dimension

The Kinematic and dynamic equations for describing the movement of WMR prototype will be derived as follows.

2.1 Kinematic Model

As passed above, the mobile robot is moving using two differential drive and on castor wheel. Thus the velocity of mobile robot can be illustrated as in Eq. 1:

$$V=\frac{V_r+V_l}{2}=\frac{r\dot{\theta}_r+r\dot{\theta}_l}{2}=\begin{bmatrix}\frac{r}{2} & \frac{\mathrm{r}}{2}\end{bmatrix}\begin{bmatrix}\dot{\theta}_r\\ \dot{\theta}_l\end{bmatrix} \tag{1}$$

The difference between angular velocity of right and left wheels can be written in relation with heading rotation angle as in Eq. 2:

$$\dot{\varphi}=\frac{V_r-V_l}{2b}=\frac{r\dot{\theta}_r-r\dot{\theta}_l}{2}=\begin{bmatrix}\frac{r}{2b} & \frac{\mathrm{r}}{2\mathrm{b}}\end{bmatrix}\begin{bmatrix}\dot{\theta}_r\\ \dot{\theta}_l\end{bmatrix} \tag{2}$$

Local coordinate system can be written as shown in Eq. 3

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\varphi}\end{bmatrix}=\begin{bmatrix}\cos(\varphi) & -d\sin(\varphi)\\ \sin(\varphi) & d\cos(\varphi)\\ 0 & 1\end{bmatrix}\begin{bmatrix}V\\ \dot{\varphi}\end{bmatrix} \tag{3}$$

Then, Eq. 3 can be written as Eq. 4 in means of angular velocity $\dot{\theta}_r$ and $\dot{\theta}_l$:

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\varphi}\end{bmatrix}=\begin{bmatrix}\frac{r}{2}\cos(\varphi)-\frac{dr}{2b}\sin(\varphi) & \frac{r}{2}\cos(\varphi)+\frac{dr}{2b}\sin(\varphi)\\ \frac{r}{2}\sin(\varphi)+\frac{dr}{2b}\cos(\varphi) & \frac{r}{2}\sin(\varphi)-\frac{dr}{2b}\cos(\varphi)\\ \frac{r}{2b} & -\frac{r}{2b}\end{bmatrix} \tag{4}$$

2.2 Dynamic Model

The dynamics of mobile robot can be derived using Lagrange equation as in Eq. 5:

$$\frac{\delta}{dt}\frac{\delta k}{\delta_{qi}} - \frac{\delta k}{\delta_{qi}} = \tau_i - A^T(q)\,\lambda \qquad (5)$$

Where, k: kinetic energy, q: coordinate system τ_i : exerted torque on the robot, $A^T(q)$: constraints of robot

The Lagrange Equation Eq. 5 can be written as in Eq. 6.

$$M(q)\ddot{q} + V(q,\dot{q}) = \tau - A^T(q)\lambda \qquad (6)$$

where:

$$M(q) = \begin{bmatrix} m & 0 & 2m_\omega d\sin(\varphi) & 0 & 0 \\ 0 & m & -2m_\omega d\cos(\varphi) & 0 & 0 \\ 2m_\omega d\sin(\varphi) & -2m_\omega d\sin(\varphi) & I & 0 & 0 \\ 0 & 0 & 0 & I_w & 0 \\ 0 & 0 & 0 & 0 & I_w \end{bmatrix}$$

$$V(q,\dot{q}) = \begin{bmatrix} 2m_\omega d\dot{\varphi}^2\sin(\varphi) \\ 2m_\omega d\dot{\varphi}^2\cos(\varphi) \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad \lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} \quad \tau = \begin{bmatrix} \tau_r & 0 \\ 0 & \tau_l \end{bmatrix}$$

Where: τ is applied force, M (q): Positive definite inertia matrix, V (q,$\dot{q}$): centrifugal and Coriolis matrix, E (q): Input transformation matrix.

2.3 Design of Controller:

The path of mobile robot is controlled using Proportional–derivative controller, Active Force Control and combination strategy that implement PD and AFC together as shown in Fig. 2.

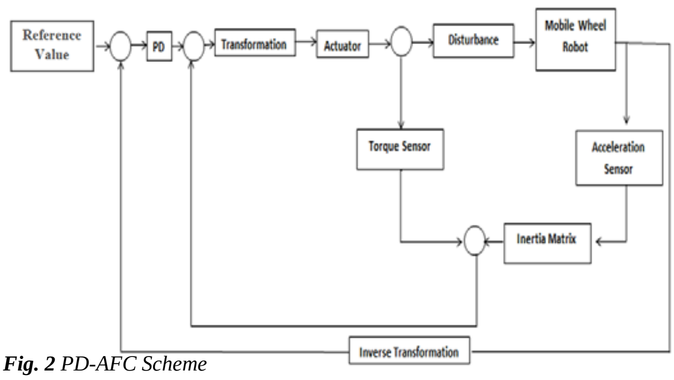


Fig. 2 *PD-AFC Scheme*

PD Controller operates based on kinematic parameters and it can be used to minimize the position and direction errors during path control. This controller is used as reference value for Active Force Control scheme after multiply by the estimated inertia matrix. Eqs. 7-9 shows the design of this PD controller.

$$\dot{x}_{error} = (\dot{x}_{ref} - \dot{x}_{act})[\,k_p\,] + [\,k_d\,]\left[\frac{d_{\dot{x}_{ref}-\dot{x}_{act}}}{d_t}\right] \qquad (7)$$

$$\dot{y}_{error} = (\dot{y}_{ref}\dot{y}_{act})[\,k_p\,] + [\,k_d\,]\left[\frac{d_{\dot{y}_{ref}-\dot{y}_{act}}}{d_t}\right] \qquad (8)$$

$$\dot{\varphi}_{error} = (\dot{\varphi}_{ref} - \dot{\varphi}_{act})[\,k_p\,] + [\,k_d\,]\left[\frac{d_{\dot{\varphi}_{ref}-\dot{\varphi}_{act}}}{d_t}\right] \qquad (9)$$

Subscripts *ref* refer to the input values and the subscripts *act* refer to the output values. The comparison between reference and actual values evaluates the stability of the control system. The smaller the tracking error, the better the motion control of a mobile robot. k_p is a proportional gains and it can be obtained by multiply an estimated value chosen arbiter using try-error method. k_d is a differential gain which can be obtained by multiply $\frac{d_u}{d_t}$ with an estimated value chosen arbitrary using try-error method.

AFC Control Strategy is the inner loop of PD-AFC controller which depends on the angular acceleration of the wheels and Inertia Matrix IN. IN is very important in the AFC strategy and needs to be estimated using Artificial Methods. Fuzzy Logic Toolbox (FL) has been chosen for estimating the inertia matrix because it is simple and functional comparing with other method. From [2], it can be found that AFC control strategy works effectively if the minimum and maximum values of IN is located in the range as in Eq. 10:

$$0.4M < IN < 0.12M \qquad (10)$$

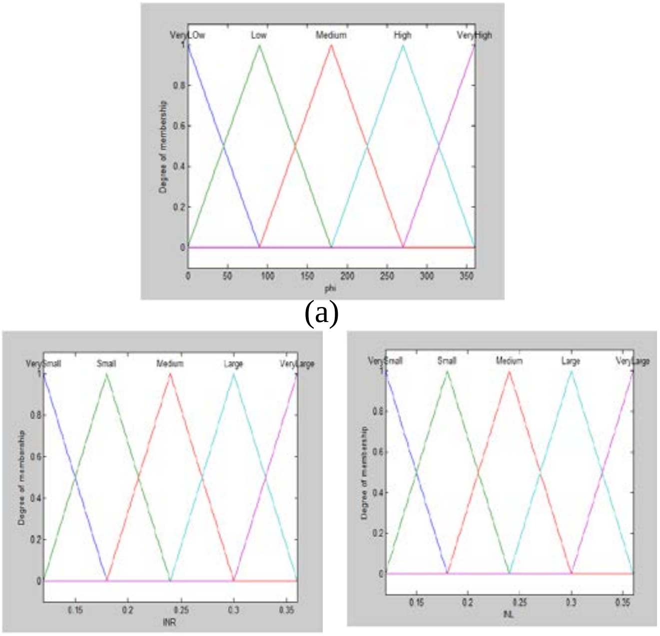
IN plays an important role in determining the estimated torque disturbance, τ_d^* as in Eq. 11

$$\tau_d^* = \tau - IN\,\ddot{\theta} \qquad (11)$$

The measurement of acceleration with estimated Inertia Matrix will be compared with applied torque to estimate torque disturbance which can be calculated as in Eq. 11.

In estimated Inertia Matrix, the heading rotation φ is used as the input of Fuzzy Logic system which has the following fuzzy set variables {Very Small, Small, Medium, Large, and Very Large} as shown in Fig. 2-a. The output of Fuzzy Logic system has two variables which are Inertia Matrix for right (INR) and left wheels (INL) as shown in Fig. 2-b, c. Both INR and INL have fuzzy set with variables {Very small, Small, Medium, Large and Very

Large}. Moreover, the five simple fuzzy rules are designed in IF-Then structure that is created inside Fuzzy Logic Toolbox as shown in Table 1. From Eq. 10, INR and INL have to be chosen between 0.12kg.m^2 and 0.36 kg.m^2.



(a)

(b) (c)

Fig. 3: Degree membership of input, φ Degree membership of output for right wheel, INR: (a) input (b) output INR (c) output INL

Table 1: Five fuzzy rules designed in IF-Then structure

1. If phi is Medium then INR is Medium and INL is Medium.
2. If phi is Very Small then INR is Very Small and INL is Very Large.
3. If phi is small then INR is small and INL is Large.
4. If phi is Large then INR is Large and INL is small.
5. If phi is Very Large the INR is Very Large and INL is Very Small.

4 Simulation Results and Discussion

To simulate the restricted environments, three kinds of trajectories with unexpected changes in their trajectory has been used to test the proposed control system. Two of them have geometrical trajectories such as circular and leaf shapes which involve a continuous and prompt change in their paths. The other one is the road roundabout path control which is the main restricted area during controlling vehicle on the road. We have implemented the proposed control system with and without disturbances to show the robustness of the control system. In each case, we have compared the reference path with PD, AFC and PD-AFC actual paths.

The simulation is performed using MATLAB/SIMULINK. The simulation setup has been adjusted as follows: Configuration Parameter:

Simulation time – Start from 0 s until 360 seconds. Solver - Fixed-step with ODE3 Auto fixed step.

Wheel Mobile Robot Parameter:

r=0.1m, b=0.02m, d=0.5m, m=36kg,

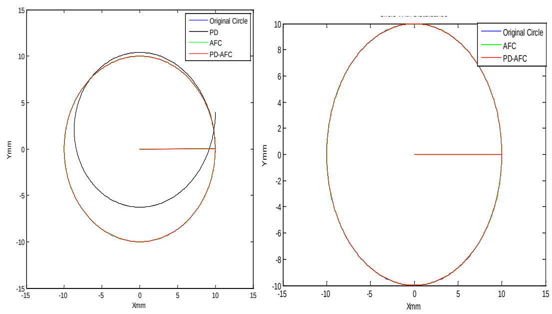
$m_w = 0.8$kg, I = 18 kg.m^2, $I_w = 0.00818$ kg.m^2,

Disturbance:

$$\tau_d = [10000 \sin t \; 10000 \cos t]^T$$

Controller Parameter: Kp for x, y and φ = 0.98, Kd for x, y and φ = 0.005

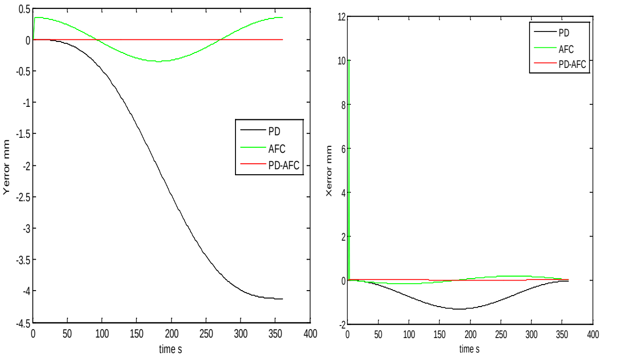
The circular path is used to test the proposed control algorithm as shown in Fig. 4. Fig. 4-a shows the circular trajectory without applying any kind of disturbances for PD, AFC and PD-AFC controllers. PD controller has a big path draft in comparison with the reference path however, AFC and PD have overlapped the original path in the whole path. Fig. 4.b shows the circular's path with presence of disturbances for AFC and PD-AFC, which are completely identical to the reference path. We didn't include PD controller due to that it has so big draft which is resulted by non-clear figure.



(a) (b)

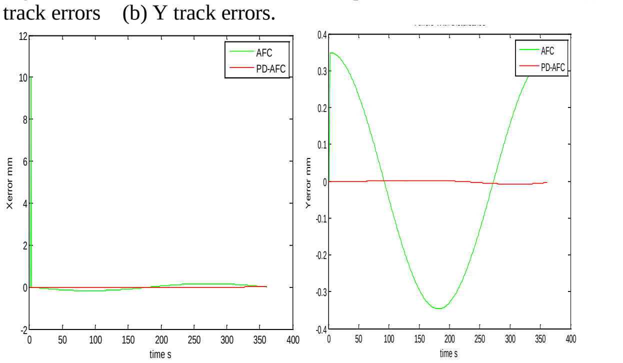
Fig. 4 Reference and Actual Circular path. (a) Without disturbance. (b) With disturbance

The estimated track errors in x and y direction without/with disturbance for the circular path has been shown Fig. 5 and 6 respectively. PD presents a bad response to the system in x and y directions even in the absence of disturbance as depicted in Fig. 5. AFC controller has a small track errors in its path especially in the beginning of the simulation; however PD-AFC controller maintain the track errors in zero level for the whole path.



(a) (b)

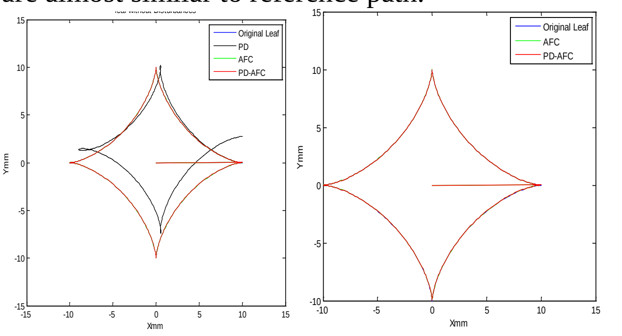
Fig. 5 shows track errors of the circular path without disturbance. (a) X track errors (b) Y track errors.



(a) (b)

Fig. 6 shows track errors of the circular path with disturbance. (a) X track errors (b) Y track errors.

In similar way, we have implemented all control schemes with simple leaf path as shown in Fig. 7. Fig. 7-a shows a comparison between the actual path for all controllers and reference path without disturbance. It can be clearly seen that PD has a big draft from the reference path whereas AFC and PD-AFC are approximately similar to reference path. With the presence of disturbance as shown in Fig. 7-b, PD is no longer useful and AFC with PD-AFC are almost similar to reference path.

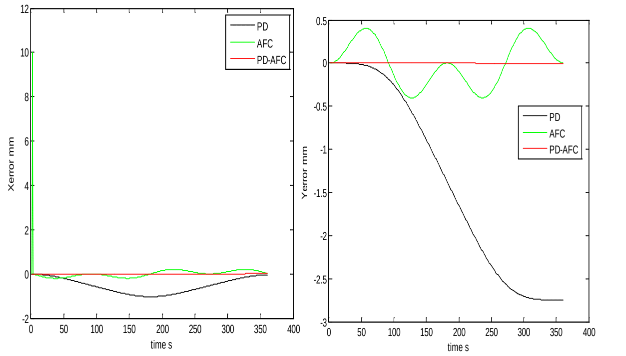


(a)

(b)

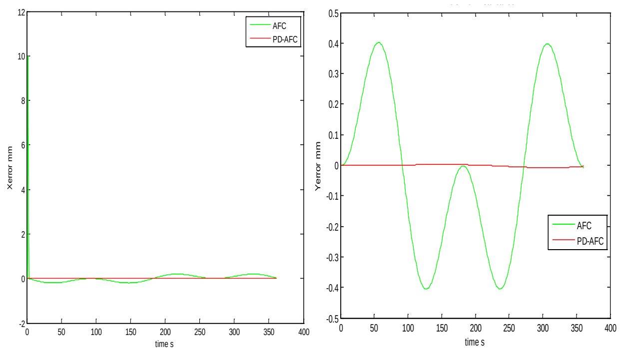
Fig. 7 Reference and Actual leaf path. (a) Without disturbance. (b) With disturbance

The track errors in x and y directions for the leaf path without disturbance are illustrated in Fig. 8. PD has the biggest track errors in x and y, however PD-AFC track errors remain at zero level. When the disturbance is applied as shown in Fig. 9, the track errors of PD become so high (in power of 10^5), but still in acceptable range with AFC controller. PD-AFC presents a higher capability to reject the effect of disturbance.



(a) (b)

Fig. 8 shows track errors of the leaf path without disturbance. (a) X track errors (b) Y track errors.



(a) (b)

Fig. 9 shows track errors of the leaf path with disturbance. (a) X track errors (b) Y track errors.

More complex path has been generated using laser simulator path planning approach [11, 12]. It has been used to find a collision free path in roundabout area as shown in Fig. 10.

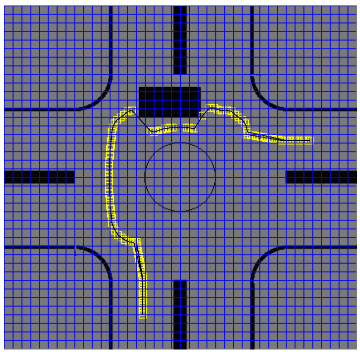
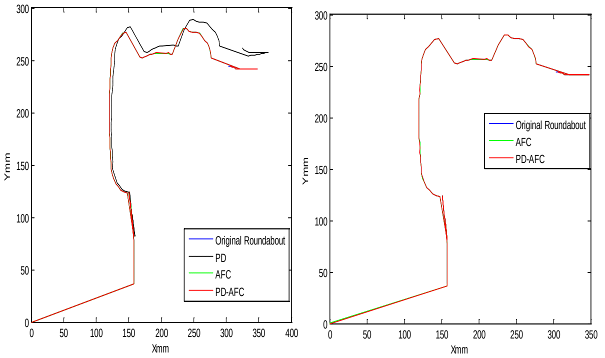


Fig. 10 Reference roundabout path generated by laser simulator

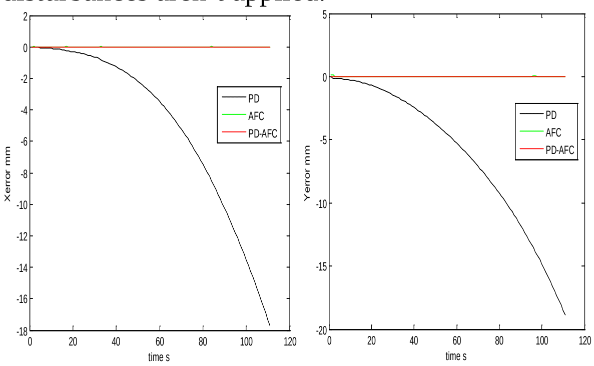
With Similarity to what have been carried out in circular and leaf trajectories, AFC and PD-AFC have the capability to track the same reference path either without disturbance as shown in Fig. 11-a or with disturbance as shown in Fig. 11-b.



(a) (b)

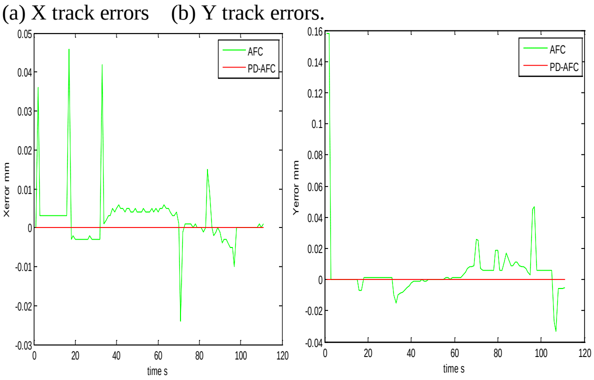
Fig. 11 Reference and Actual roundabout path. (a) Without disturbance. (b) With disturbance

The track errors in x and y direction for roundabout environment are illustrated in Fig. 12 in the case of no applied disturbance and with disturbance as shown in Fig. 13. From both Fig.12 and 13, PD-AFC can guarantee the robustness of control system against disturbance, however AFC has small track errors and still can be used alone but The PD controller can't be used even if the disturbances aren't applied.



(a) (b)

Fig. 12 shows track errors of the roundabout path without disturbance. (a) X track errors (b) Y track errors.



(a) (b)

Fig. 13 shows track errors of the roundabout path with disturbance. (a) X track errors (b) Y track errors.

4. Conclusion

Simulation of restricted environments has been presented in this paper. Two geometrical trajectories, namely circular and leaf paths that involve a continuous and unexpected changes in their paths has been used to test the suggested control scheme. A simulated roundabout as the main restricted area during controlling vehicle on the road has been also utilized to evaluate PD-AFC algorithm. The proposed control system is implemented with and without disturbances conditions to show the robustness of the control system. In all discussed cases, the reference path is compared with PD, AFC and PD-AFC actual paths. Results shows the capability of PD-AFC to eliminate the effect of disturbances and maintain the track errors in zero level.

Acknowledgment

The authors would like to thank Universiti Malaysia Pahang (UMP) and Ministry of High Education (MOHE) for providing the research grant and facilities. This research is supported by FRGS grant under (Ref: RDU160131).

References

[1] Hewit, J. R., & Burdess, J. S. Fast dynamic decoupled control for robotics, using active force control. *Mechanism and Machine Theory*, *16*(5), 535-542. 1981.

[2] Mailah, M., Pitowarno, E., & Jamaluddin, H. Robust motion control for mobile manipulator using resolved acceleration and proportional-integral active force control. *arXiv preprint cs/0601057*. 2006.

[3] Kwek, L. C., Wong, E. K., Loo, C. K., & Rao, M. V. C. Application of active force control and iterative learning in a 5-link biped robot. *Journal of Intelligent and Robotic Systems*, *37*(2), 143-162. 2003

[4] Jahanabadi, Hossein. Intelligent active force control of a human-like arm actuated by pneumatic artificial muscles.UTM Thesis. 2010.

[5] Hashemi-Dehkordi, S. M., Abu-Bakar, A. R., & Mailah, M. Reducing friction-induced vibration using intelligent active force control (AFC) with piezoelectric actuators. *Sadhana*, *37*(6), 637-655.2012.

[6] Kozłowski, K., & Pazderski, D. Modeling and control of a 4-wheel skid-steering mobile robot. *Int. J. Appl. Math. Comput. Sci*, *14*(4), 477-496.2004.

[7] Mohammed A. H. Ali, Musa Mailah, Hamedon, B., & Yussof, Z. B. Wheeled Mobile Robot Path Control in a Complex Trajectory using HybridMethods. International conference omn robotics, control and manufacturing ROCOM 15. 2015.

[8] Kwek, L. C., Kang, C. C., Loo, C. K., & Wong, E. K. Implementation of evolutionary active force control in a 5-link biped robot. *Intelligent Automation & Soft Computing*, *11*(3), 167-178.2005.

[9] Mailah, M., Abdullah, S., & Hing, T. H. Tracking Performance on Feedfoward Model Base Active Force Control of Mobile Manipulator using Matlab and Adams. *Recent Advances in Electrical Engineering Series*, (11). 2013.

[10] Onn, N., Hussein, M., TANG, C. H. H., Zain, M. Z. M., Mohamad, M., & Ying, L. Active Force Control with Nonlinear Predictive Control based on Receding-Horizon Cost Function Optimization for Five-Link Biped Model in Sagittal Plane.2013.

[11] Mohammed A. H. Ali, Musa Mailah, Tang Howe Hing, " A novel Approach for Visibility Search Graph Based Path Planning". 13th International conference on Robotics, Control and Manufacturing Systems. Kuala-lumpur, pp 44-49, 2-4th April, 2013.

[12] Mohammed A. H. Ali, Musa Mailah, Tang Howe Hing, "Implementation of Laser Simulator Search Graph Approach for Detection and Path Planning in Roundabout Environments". WSEAS Transactions on Signal Processing. Vol. 10, pp 106-115, 2014.