Wheeled Mobile Robot Path Control in a Complex Trajectory using HybridMethods

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Abstract—A robust control algorithm for tracking the mobile robot in a pre-planned path during passing through complicated environments such as in roundabout is presented in this paper. The proposed algorithm is derived from the kinematic and dynamic of 3wheeled Non-holonomic mobile robot motion. The control scheme is performed using Resolved Acceleration Control, Active Force Control strategy or mixed of them in Simulink-MATLAB, which are compared with each other in the matter ofenabling the robot to follow the predefined path while applying disturbances. Results show the capability of this controller to track the robot on the pre-defined path and remove the effect of the disturbances.

Key-words:— Non-holonomicWheeled Mobile robot, Lagrang-Eular Equation, Resolved Acceleration Control, Laser Simulator, Active Force Control Strategy, Fuzzy Logic.

1 Introduction

Nowadays, mobile robots are a common use in many applications that represent a hazardous, complex, high accurate or hard tasks in worldwide fields, like aerospace, under-water, military, medicine, inspection, mining ….etc. Usually the robot is supposed to navigate autonomously either in structured or non-structured environments; both need high robust control to determine its path within terrain and avoiding obstacles. In some conditions like road environments, it is important to control robustly the robot in the pre-planned path; otherwise it will crash cars or people.

Complex trajectory is occurred when there are open spaces areas in the path of the robot such as in roundabout. The path planning in such area is restricted to the road roles, undetectable area in by sensors and choosing the right branch to get out from roundabout. This path needs a high accurate control system to be performed; otherwise it can crash other vehicles or collide with the road's infrastructure [1].

Different methods and techniques have been investigated to solve the problems of mobile robot motion control; some of them depend only on the kinematics of the mobile robot; others on the dynamics, or combination between them.

A wheel controlling with feed-forward compensation of dynamics is used for servo control of an autonomous mobile robot [2], which is adaptive to variations of movement using the recursive least square method for online parameters estimator. Fuzzy logic controller with reference speed derived from the curvature of the detected trajectory by camera and image processing is used for control of mobile robot [3]. Fuzzy logic controller is preferred based on some properties like non-linear nature of the FLC, a fast dynamic response, which resulted by an accurate dynamic model of system [4].An adaptive method using a kinematic and torque controller based on Fuzzy Logic reasoning is used for intelligent control of an autonomous Mobile Robot [5]. Neural networks controller is utilized for controlling the motion of mobile robot [6] through using one layer to define the relationship between the linear velocities and the error positions of mobile robot.A cross-coupling method [7] is used in differential drive for controlling the velocity of both motors, in which the control loop of each motor uses the position errors of the other one. Fuzzy logic controller [8] is implemented for controlling a wheeled mobile robot motion in unstructured environments with obstacles and slopes. A stable tracking control system [9] is used for adjusting the linear and rotational velocities of mobile robot using a Liapunov function, which depends on linearizing of kinematics model with feedback control. An approach based on feedback sliding mode control [10] is used for stabilizing of non-holonomic mobile robot. Sliding-mode control method [11] is utilized for stabilization and tracking of non-holonomic mobile robots using kinematics in polar coordinates. The back-stepping control approach with integration of a kinematic and a torque controller [12] has been used for control of non-holonomic mobile robots.

AFC controller has been proposed by [13] and experimentally implemented with a lot of mobile manipulator dynamics system, which resulted by high robust control to the system especially with existence of disturbances [14].

In this paper, three controller has been used for robot path control namely; RAC, AFC, and a combination RAC-AFC. RAC is common used for controling the position and orientation errors during movements however the AFC is useful to be utilized with dynamic disturbances. The RAC-AFC control system scheme consists of two feedback loops: external and internal loop. The external loop is used for controlling the kinematics parameters by the Resolved Acceleration Control and the internal loop is used for controlling the dynamics parameters and disturbances of robot by AFC controller.

The control of mobile robot in a complix path in some dangerous areas such as in roundabout during path execution still a complicated problem in robot researches,since it needs to maintain the track errors at zero level [1]. Here in this paper, it is suggested to use our laser simulator approach for path planning in roundabout, which is remarked as a complex environments and still not modeled yet. The robust control strategy is applied to execute the path in the roundabout environments; which is the contribution of this paper.

2 Modeling of Non-Holonomic Wheeled Mobile Robot Laser

The robot is assumed to be moved in a flat plane where the motion can be described in x and y direction using three wheels; two differential wheels and Castor as in Fig. 1. The movement is generated by motors, which switch the right wheeled by angular velocity $\dot{\theta}_r$ and switch the left one with $\dot{\theta}_l$. The heading direction φ determines the rotation of mobile robot in counter clockwise. The robot motion can be described in two coordinate systems: global coordinate system X, Y axis and Local coordinate system W,V as in Fig. 1. In the global coordinate system, the motion can be obtained in three axises q= [xc, yc, φ]^T as in Fig. 1, whereas the local coordinate system has only two axisesw,v. The center of Non-holonomic mobile robot has some constraints to its movements, due that the wheels are assumed to be moved with pure rolling, without slipping on the ground and it can move only in the normal of the axis of driving wheels (no movement in sidewise). This constraints can be written as in Eq. 1

$$A(q)\dot{q} = \begin{bmatrix} -\sin(\varphi) & \cos(\varphi) & -d & 0 & 0 \\ \cos(\varphi) & \sin(\varphi) & -b & -r & 0 \\ \cos(\varphi) & \sin(\varphi) & b & -r & 0 \end{bmatrix} \begin{bmatrix} \dot{x} & \dot{y} & \dot{\varphi} & \dot{\theta}_r & \dot{\theta}_l \end{bmatrix} \tag{1}$$

Where, L -: Length of the robot. , 2b:Distance between the two wheels. , r: Radius of the driving wheels (both wheels are with same radius)., d :Displacement between the driving wheel shaft and the mass centre c of the mobile robot.

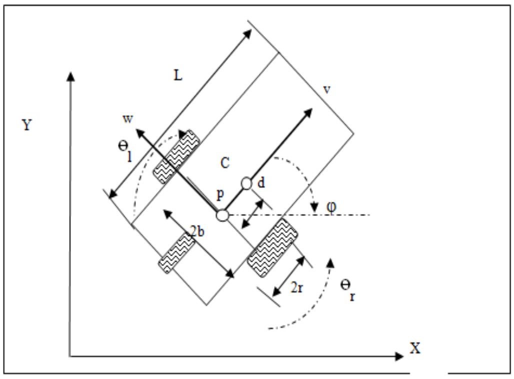


Fig. 1 illustrate mobile robot dimension with global and local coordinate system.

2.1 Robot Kinematics and Dynamics

The mobile robot is driven by two differential wheels with caster wheel in rear as in Fig. 1. The right wheel is led by velocity equal to $V_r = r\dot{\theta}_r$ and the left wheel by $V_l = r\dot{\theta}_l$. Therefore the velocity of mobile of mobile robot can be written as in Eq. 2:

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

The angular velocity of the heading rotation is then the difference between the angular velocity of right wheel and the left wheel, which can be calculated as in Eq. 3:

$$\dot{\varphi} = \frac{V_r - V_l}{2b} = \frac{r\,\dot{\theta}_r - r\,\dot{\theta}_l}{2b} = \begin{bmatrix} \frac{r}{2b} & -\frac{\mathrm{r}}{2\mathrm{b}} \end{bmatrix} \begin{bmatrix} \dot{\theta}_r \\ \dot{\theta}_l \end{bmatrix} \qquad (3)$$

The velocity of the robot in a global coordinate can be described in local coordinate system by the means of angular velocity $\dot{\theta}_r$ and $\dot{\theta}_l$ as in Eq. 4:

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

2.2 Mobile Robot Dynamics

The dynamic equations of mobile robot can be determined using Newton's law or Eular-Lagrang equation. In this research, the lagrang equation is used to derive the dynamics equations of the robot:

$$\frac{\partial}{dt}\frac{\partial k}{\partial q_i} - \frac{\partial k}{\partial q_i} = \tau_i - A^T(q)\lambda \qquad (5)$$

where k is the kinetic energy and q is the coordinate system τ_i is the exerted torque on the robot, A^{T}(q) is the constriats of robot movement. By deriving the Lagrange equation, the total Lagrange equation can be written as in Eq. 6:

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

Where:

$$M(q) = \begin{bmatrix} m & 0 & 2\mathrm{m}_{\omega}\mathrm{dsin}(\varphi) & 0 & 0 \\ 0 & \mathrm{m} & -2\mathrm{m}_{\omega}\mathrm{dcos}(\varphi) & 0 & 0 \\ 2\mathrm{m}_{\omega}\mathrm{dsin}(\varphi) & -2\mathrm{m}_{\omega}\mathrm{dsin}(\varphi) & \mathrm{I} & 0 & 0 \\ 0 & 0 & 0 & \mathrm{I}_{\mathrm{W}} & 0 \\ 0 & 0 & 0 & 0 & \mathrm{I}_{\mathrm{W}} \end{bmatrix}$$

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

$A^T(q)$=Transpose of the constraints equation A(q) as in Eq. 1.

m : total mass of Mobile Robot = *mc* + 2*mw*, *mc* : the mass of the platform without the driving wheels and the DC motors, *mw*: the mass of the driving wheels and the DC motors., *I:* total moment of inertia of mobile robot = *Ic*+ 2*mw* (d^2+ b^2) + 2*Im*, *Ic*: the moment of inertia of the body of robot without the driving wheels and the motors about axis passed through *P.*, *Iw*: the moment of inertia of each wheel and the motor rotor about the wheel axis., *Im*: the moment of inertia of each wheel and the motor rotor about the wheel diameter., τ_r : the torque exerted on wheel axis by right motor., τ_l: the torque exerted on wheel axis by left motor., λ: the Lagrange multiplier coefficient.

3. Design of Controller

The path of mobile robot is controlled using Resolve Acceleration Control, Active Force Control and acombination of them RAC-AFC strategy. In RAC-AFC, there are two feedback loops in the control scheme, external and internal loop as in Fig. 2; the external loop is used for controlling the kinematics parameters by the RAC and the internal loop is used for controlling the dynamics of robot by AFC contrller. Transformation in Fig. 2 is reffered to the relation between the global and local coordinate systes as in Eq. 4.

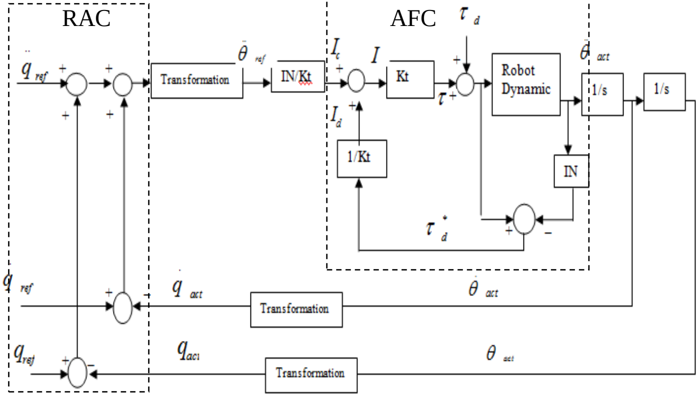


Fig. 2: Illustrate the RAC-AFC control Scheme.

3.1 RAC Control Strategy

This controller proposed by [16] to control the hand gripper. This controller is working based on minimizing of the position and orientation errors to zero, which needs to apply suitable torque or forces to the system. Eqs. 7-9 describe this controller.

$$\ddot{x}_{act} = \ddot{x}_{ref} + Kd(\dot{x}_{ref} - \dot{x}_{act}) + Kp(x_{ref} - x_{act}) \quad (7)$$

$$\ddot{y}_{act} = \ddot{y}_{ref} + Kd(\dot{y}_{ref} - \dot{y}_{act}) + Kp(y_{ref} - y_{act}) \quad (8)$$

$$\ddot{\varphi}_{act} = \ddot{\varphi}_{ref} + Kd(\dot{\varphi}_{ref} - \dot{\varphi}_{act}) + Kp(\varphi_{ref} - \varphi_{act}) \quad (9)$$

Where suscripts *ref* and *act* refer to input and output respectively, *Kd* and *Kp* are the differential and proportional gains respectively. Fig.2 show this controller.

3.2 AFC Strategy

AFC controller has been proposed by [12] and experimentally implemented with several dynamic systems, which robustly eliminate the effects of disturbances [13-15,17,18]. It is the inner loop in the proposed controller and it depends on the angular acceleration of the of wheels motors. In real-world environment, AFC controller consists of actuators that apply torque to the driving wheels and sensors that measure the angular acceleration of wheels. The measured acceleration with estimated Inertial matrix is compared with applied torque as in Eq.18. By estimating the Inertial matrix using Artificial Intelligence methods, the controller can very rapidly and effectively compensate the distubances. In simulation, these measurements are assumed to be perfectly known. The equation that estimated the disturbance can be written as in Eq. 10:

$$\tau_d^* = \tau - IN\,\ddot{\theta} \quad (10)$$

Where τ_d^* is the estimated torque disturbance effected on the wheels. τ is the torque of actuator, which can be calculated in DC motors using the following equation:

$\tau = K_t I$, I is the current of DC motor. *IN* is the estimated inertial matrix.

The estimated Inertia matrix forboth experiments has been calculated using fuzzy logic approach with following memberships as in Fig. 5. Depending on that, the inertial Matrix M(q) in Eq. 9, can change only regarding to (φ) and the others values are constant, we choose φ as the input for FL, which is fuzzed to a fuzzy set with suitable linguistic variables as following: φ={Very low, Low, Medium, High, Very High}. In otherwise, the output of FL is fuzzed into two output sets with suitable linguistic variables, which can be written as following INR/INL={ Very small, Small, Medium, Large, Very large}.

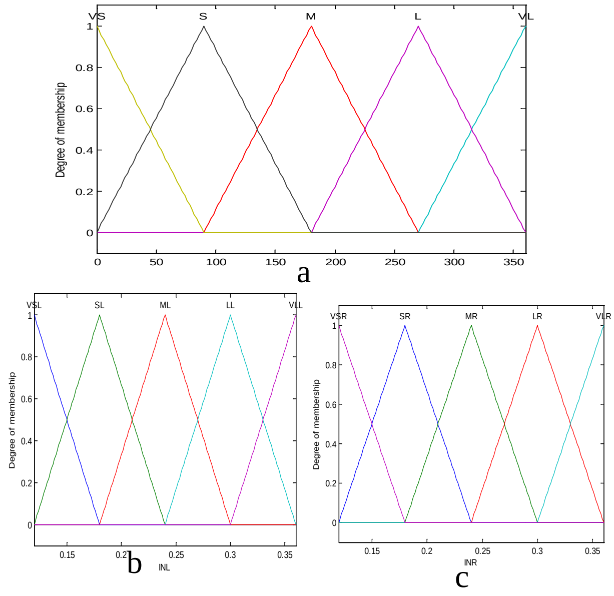


Fig. 5: Membership functions of system input and output: (a) input (φ). (b) output INR. (c) output INL.

In this simulation, the fuzzy inference system is done using *Mamdani* type as follows:

1. *If (phi is M) then (INR is MR)(INL is ML)*
2. *If (phi is VL) then (INR is VSR)(INL is VLL)*
3. *If (phi is L) then (INR is SR)(INL is LL)*
4. *If (phi is H) then (INR is LR)(INL is SL)*
5. *If (phi is VH) then (INR is VLR)(INL is VSL)*

4Path control Simulation Results and Discussion

The simulation is done using Matlab/simulink for the above-metioned pre-defined path with discrete values simulation with the following parameters:

Integration algorithm: ODE3 (Bogacki-Shanpine)
Simulation type: Fixed step
Fixed step size: Auto
WMR Parameters:

r = 0.15 m, b = 0.75 m, d = 0.03 m, m = 31.0 kg, m_w= 0.5kg, I=15.625 kg.m^2 ,I_w=0.005kg.m^2

Controller Parameters:

Kpx = 2/s^2, Kpy = 2/s^2, Kpφ= 2/s, Kdx = 1, Kdy= ,Kdφ= 1 (for the RAC part)

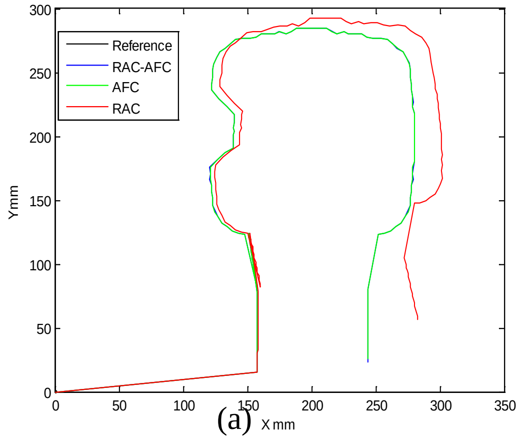
$K_t = \begin{bmatrix} 0.263 \\ 0.263 \end{bmatrix}$ N/A (obtained from catalogue of suitable DC motor for AFC part).

Disturbance Models Parameters: Several constant torque disturbances and Harmonic torque disturbances were applied to the control system.

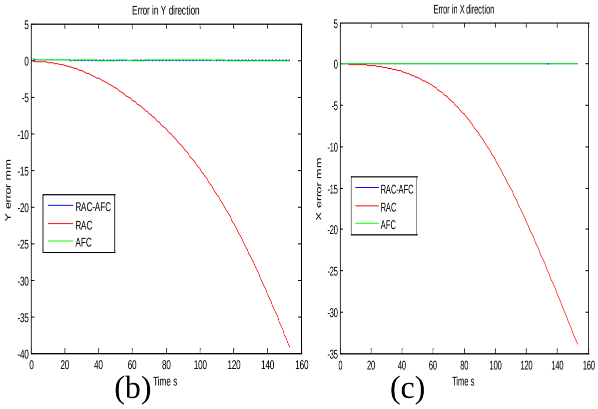
We have implemented three types of controllers and compare them with reference trajectory:

- RAC based kinematic controller.
- AFC based dynamic controller.
- RAC-AFC controller.

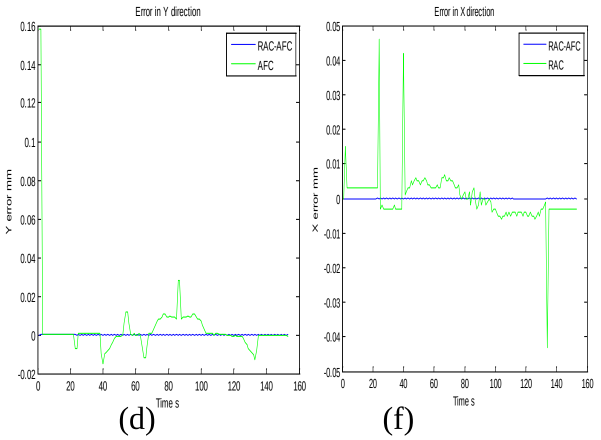
Fig. 3 bellow shows the actual trajectory of all controllers without disturbance for the predefined path of mobile robot. RAC presents reckoning errors that increase incrementally during tracking the path with high track errors in x(30mm) and y(35mm). However the difference between the reference and actual path of AFC, RAC-AFC are two small and therefore they are overlapped each other; where the track errors in the power of 10^{-2} mm. we can notice that a big shoots at the beginning of AFC controller will be occurred because there still no output from AFC controller loop, whereas at RAC and RAC-AFC, there was no overshoot due to the effect of kinematic controller at the beginning.



(a)



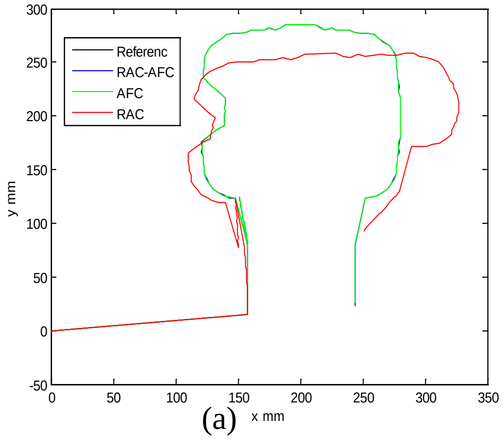
(b) (c)



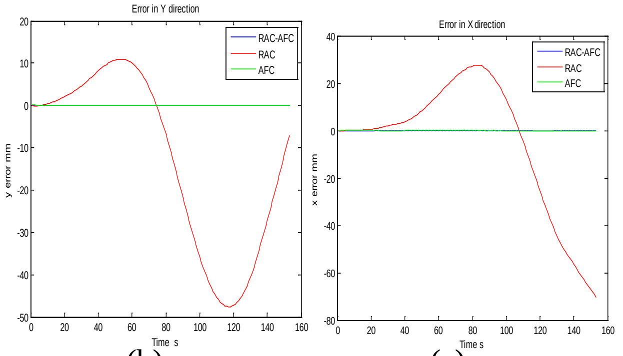
(d) (f)

Fig. 3: Illustrate the result of AFC and RAC-AFC controller simulationwithout disturbance. (a) the trajectory of mobile robot. (b) y track errors for RAC, AFC and RAC-AFC. (c) y track errorsfor AFC and RAC-AFC. (d) x track errors for RAC, AFC and RAC-AFC (e)x track errorsfor AFC and RAC-AFC.

Fig. 4 bellow shows the actual trajectory of all controllers with constant disturbance $\tau_d = [0.1 \quad 0.1]^T$ applying to the predefined path of mobile robot. RAC presents big deviation errors during tracking the path with high track errors in x(50mm) and y(60mm). However the difference between the reference and actual path of AFC, RAC-AFC still two small and therefore they are overlapped each other; where the track errors in the power of 10^{-2} mm at x and y directions.



(a)



(b) (c)

Fig. 4: Illustrate the result of RAC, AFC and RAC-AFC controller simulationwith disturbance 0.1 N.m. (a) the trajectory of mobile robot. (b) x track errors(c) y track errors

4. Conclusion

TheRAC, AFC and RAC-AFC controllers have been used to track the robot on the pre-defined trajectory. The parameters of the controllers are derived from kinematics and dynamics equations that describe the robot motion with non-holonomics constraints. The fuzzy logic reasoning is implemented to find the inertial matrix for the calculation of the applied torque. From simulation results, it has seen that, there is no difference between the reference and actual path without disturbance for AFC and RAC-AFC, however there was a sizable draft in RAC. When applying a constant disturbance, there was a big deviation between the reference and actual track in RAC, but it doesn't affect to AFC or RAC-AFC controller. In general, AFC and RAC-AFC controllers present the capability to eliminate the effect of disturbances on the system.

References

[1] Mohammed A. H. Ali, Autonomous Mobile Robot Navigation and Control in the Road Following and Roundabout Environments Incorporating Laser Range Finder And Vision System. Ph.D Thesis UTM, 2014.

[2] K. C. Koh' and H. S. Cho “Wheel Servo Control based on Feedforward Compensation for an Autonomous Mobile Robot”. Technical Report, Department of Precision Engineering & Mechatronics School of Mechanical Engineering KAIST, Korea.

[3] M. Gunes, F. Baba . “Speed And Position Control Of Autonomous Mobile Robot On Variable Trajectory Depending On Its Curvature”. Journal of scientific and industrial research vol. 68 June 2009, pp 513-521.

[4] T. H. Lee, F. H. F. Hung P. K. S. Tam. “Position Control for Wheeled Mobile Robots Using a Fuzzy Logic Controller”. The Hong Kong Polytechnic , University, Hung Hom, Kowloon , Hong Kong.

[5] L. Astudillo, O. Castillo, P. Melin, A. Alanis, J. Soria, L. Aguilar. Intelligent Control of an Autonomous Mobile Robot using Type-2 Fuzzy Logic. Division of Graduate Studies and Research in Tijuana Institute of Technology, Mexico

[6] JasminVelagic, Nedim Osmic, and BakirLacevic.“Neural Network Controller for Mobile Robot Motion Control”.World Academy of Science, Engineering and Technology 47 2008.

[7] J. Borensteinand Y. Koren, Motion Control Analysis of a Mobile Robot. Transactions of ASME, Journal of Dynamics, Measurement and Control, Vol. 109, No. 2, pp. 73-79.

[8] GyulaMester. “Intelligent Mobile Robot Motion Control inUnstructured Environments”.ActaPolytechnicaHungarica Vol. 7, No. 4, 2010.

[9] Y. Kanayama, Y. Kimura, F. Miyazaki T. Noguchi, “A Stable Tracking Control Method For a Non-Holonomic Mobile Robot”, Proc. IEEE/RSJ Int. Workshop on Intelligent Robots and Systems, Osaka, Japan, pp 1236- 1241, 1991.

[10] A. BlochS. Drakunov “stabilization of a nonholonomic system via sliding modes”. Proceedings of the 33rd Conference on Decision and Control Lake Buena Vista, FL - December 1994.

[11] D. Chwa. Sliding-Mode Tracking Control of Nonholonomic Wheeled Mobile Robots in Polar Coordinates. IEEE transactions on control systems technology, vol. 12, no. 4, july 2004.

[12] R. Fierro and F. L. Lewis. “Control of a Nonholonomic Mobile Robot: Backstepping Kinematics into Dynamics”. *Journal of Robotic Systems* 14(3), 149–163 (1997)

[13] Hewit, J. R. and Burdess, J. S. (1981). Fast Dynamic Decoupled Control for Robotics using Active Force Control. *Trans. Mechanism and Machine Theory*, 16(5), 535-542.

[14] Hewit, J. R. and Marouf, K. B. (1996). “Practical Control Enhancement via Mechatronics Design.*IEEETrans.Industrial Electronics*”, 43(1), 16-22.