13

Type-2 Fuzzy Control of an Automatic Guided Vehicle for Wall-Following

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1. Introduction

Fuzzy logic inference system (FIS) has been widely applied to the controller design for automatic guided vehicles (AGV) because FIS allows easier controller design under uncertainty and nonlinearity (Hwang et al., 2007; Godjevac & Steele, 1999; Baturone et al., 2008; Er &Deng, 2004; Ng & Trivedi, 1998). Wall following is a commonly adopted scheme for an AGV to navigate in the indoor or outdoor environments. Sonar system is usually the most popular hardware system installed on the AGV for wall following due to its cost-effective functionality and computational efficiency. There has been some research applying FIS to the sonar-based wall following task (Tsui et al., 2008; Li et al., 2003; Juang & Hsu, 2009). The sonar constantly transmits ultra-sound signals during the wall following process. The ultra-sound signals cannot go through most of the objects, walls or structures in the environment, and thus are reflected back to the sonar. By calculating the difference between the time when the ultra-sound signals are transmitted and are received, the AGV is able to constantly detect the distance between the AGV and the object the ultra-sound signals are reflected from. For the wall following, the AGV is controlled to navigate along the wall while maintaining a fixed distance based on the received ultra-sound signals. If the surface or texture of the wall varies as AGV navigates in the environment, the ultra-sound signals might not be directly reflected back to the receiver or the intensity of received signals might not be constant all the time. The time difference of the transmitted and received ultra-sound signals is determined by calculating the time when the transmitted signal is above a threshold and the time when the received signal is above another threshold. The deflection of the ultra-sound signals due to the variation of object surface and the reduction of reflected signals due to the surface texture and material characteristic will cause the uncertainty of distance detection based on reflected ultra-sound signals. In other words, the calculated distance is corrupted by inevitable noise and disturbance contained in the received ultra-sound signals.
Although fuzzy controllers are credited with a high degree of reliability for controlling such a complicated system as AGV, the type-1 fuzzy controller sometimes is not robust enough to cope with the uncertainty existed in the noise-corrupted sonar signals. In this paper, a type-2 fuzzy controller (Mendel, 2001; Mendel & John, 2002) is proposed to control both the left and right drive wheel of an nonholonomic AGV for the wall following. It will be shown in this paper that the proposed type-2 fuzzy controller resolves the inevitable noise problem due to its flexibility of processing controller’s input and output signals with uncertainty and

its robustness held in the type-2 fuzzy control system. AGV usually works in uncertain environments with noisy sensing data and has nonlinear interactions with the changing environments. In some situations or applications, the type-2 FIS is more suitable to being applied to the design of AGV controllers. Recently, some research has applied the type-2 FIS to the control of AGV. In (Hagras, 2004), a hierarchical type-2 fuzzy controller was design for a mobile robot navigating in new environments. In (Zhang & Wang, 2007), a type-2 fuzzy controller was successfully designed to control the periodic walking motion for a biped robot. The type-2 FIS was also integrated with a neural network. A type-2 fuzzy-neural network was designed for the environment recognition as part of the navigation control of a mobile robot (Nurmaini et al., 2009). To reduce the heavy computational efforts in type-reduction process of a type-2 FIS, several efficient type-reduction schemes have been proposed to simplify the computation for defuzzification (Karnik & Mendel, 2001; Wu & Tan, 2005; Wu & Mendel, 2002).

2. Problem statement and interval type-2 fuzzy controller

Given that an AGV is to navigate within an environment by following walls or structures in the environment. For the convenience and simplicity of description, the wall or structure for the AGV to follow is called the wall in the rest of this paper. The AGV is controlled to maintain constant distance between the AGV and the wall despite that the texture and the surface of the wall may vary to some extent during the wall following process. Assume that the sonar system is utilized on AGV to detect the distance between the wall and the AGV. As shown in Fig. 1, the AGV used in this paper is equipped with 12 sonar transceivers around the vehicle body.

In this paper, a fuzzy controller is designed to control the steering of both AGV's drive wheels for wall following despite the noise and disturbance that might cause miscalculation of distance between the AGV and the wall. A type-2 FIS is adopted in the proposed fuzzy controller due to the flexibility to describe controller's input and output signals and the robustness held in the type-2 fuzzy control system. It is known from Fig. 1 that both front and rear sonar transceivers numbered 1 and 9 are used for following the right wall while two sonar transceivers numbered 6 and 14 are used for following the left wall. Denote D as the distance the AGV is controlled to keep away from the wall during the wall following process. Let T be the sampling interval, $d_1(kT)$ and $d_2(kT)$ be the measured distance based on the ultra-sound signals received by the front and rear sonar transceivers, respectively, at *k-th* sampling interval. For the convenience of notation, the sampling interval T is omitted for the following signal notations. If $e_1(k) = D - d_1(k)$ and $e_2(k) = D - d_2(k)$, the type-2 fuzzy controller for the wall following is to control the AGV's increment of rotation angle, $b(k) \equiv \Delta\theta(k)$ as following:

$$if\ e_1(k)\ is\ \tilde{A}_1^{(i_1)}\ and\ e_2(k)\ is\ \tilde{A}_2^{(i_2)}\ then\ b(k)\ is\ \tilde{B}^{(i_1 i_2)} \tag{1}$$

where $\tilde{A}_1^{(i_1)}$, $\tilde{A}_2^{(i_2)}$ are the i_1*-th* and i_2*-th* type-2 fuzzy sets for controller inputs e_1, e_2, while $\tilde{B}^{(i_1 i_2)}$ is the corresponding output $i_1 = 1 \ldots N_1$, $i_2 = 1 \ldots N_2$, and $i_3 = 1 \ldots N_3$. Assume that N_1, N_2 and N_3 type-2 fuzzy sets are defined to describe the fuzzy inputs e_1, e_2 and output y, respectively. M fuzzy rules are assigned in the fuzzy controller. As the rotational increment $b(k)$ is determined by the fuzzy controller at every *k-th* sampling interval, AGV's rotation angle at *(k+1)-th* sampling interval is defined as:

$$\theta(k+1) = \theta(k) + b(k) = \theta(k) + \Delta\theta(k) \tag{2}$$

To increase the computational efficiency of the fuzzy controller, the input type-2 fuzzy sets are defined as interval type-2 fuzzy sets, i.e.,

$$\tilde{A}_h = \sum_{e_h \in E_h} \mu_{\tilde{A}_h}(e_h) \Big/ e_h = \sum_{e_h \in E_h} \Big(\sum_{q_h \in \left[\underline{\mu}_{\tilde{A}_h}, \overline{\mu}_{\tilde{A}_h}\right]} 1/q_h \Big) \Big/ e_h \text{ , } h = 1\ldots2. \tag{3}$$

where $\mu_{\tilde{A}_h}(e_h)$ is the secondary membership of the type-2 fuzzy set $\tilde{A}_h$ for the *h-th* input signal e_h, and E_h is universe of discourse of e_h. The primary membership values are set to be 1 for primary variable $q_h \in [\underline{\mu}_{\tilde{A}_h}, \overline{\mu}_{\tilde{A}_h}]$.

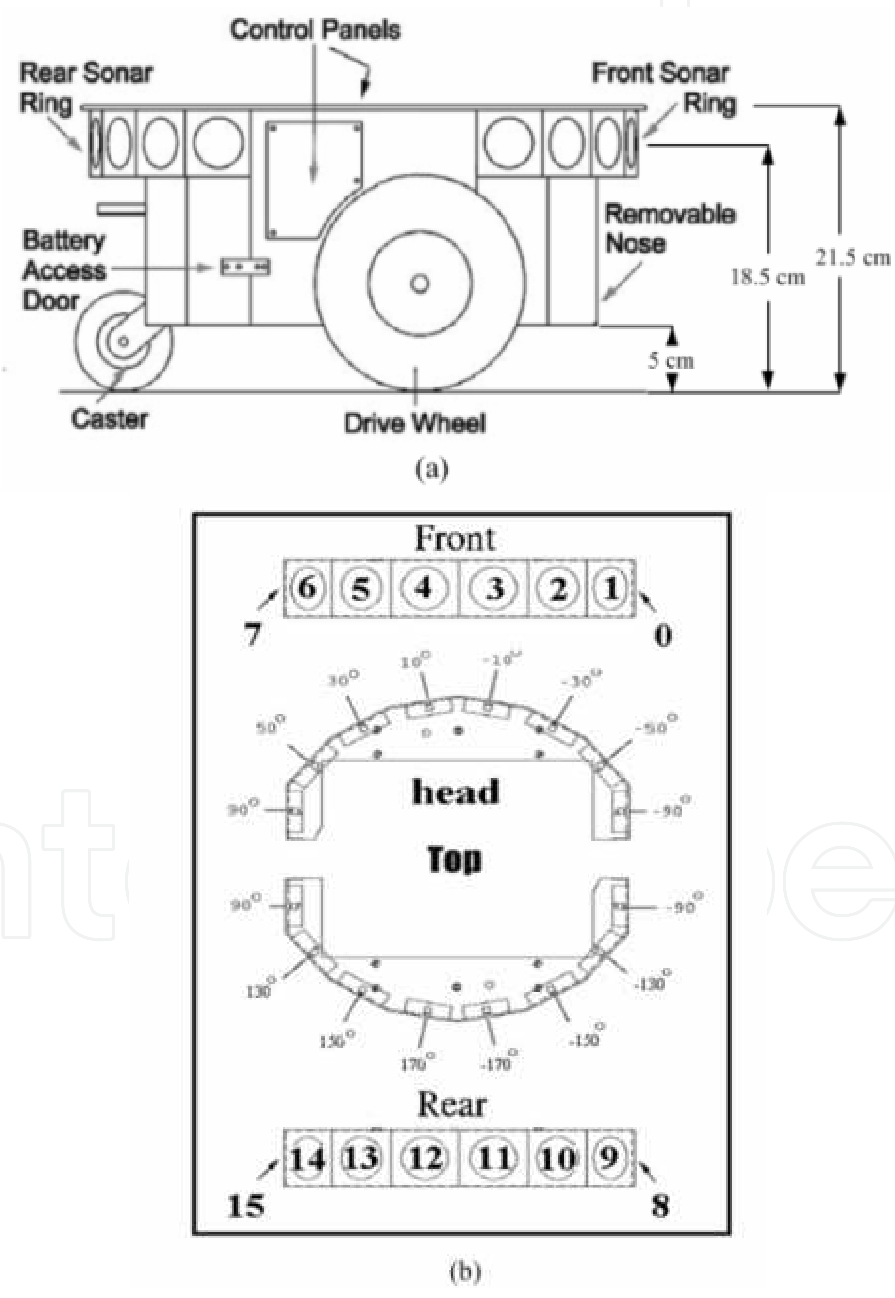


Fig. 1. (a) Side view of an AGV. (b) Sonar transceivers around the AGV.

3. Calculation of AGV's rotational increment

The measured signals $e_1(\cdot)$ and $e_2(\cdot)$ are transformed to be type-2 fuzzy singletons. At every *k-th* sampling interval, assume that the $e_1(k) = e_1^{'}$ and $e_2(k) = e_2^{'}$. The degree of firing (DOF) of every fuzzy rule in the fuzzy rule base $\Gamma^{(i_1 i_2)}(e_1^{'}, e_2^{'}) = [\underline{\gamma}^{(i_1 i_2)}(e_1^{'}, e_2^{'}), \overline{\gamma}^{(i_1 i_2)}(e_1^{'}, e_2^{'})]$,where

$$\underline{\gamma}^{(i_1 i_2)} = \underline{\mu}_{\tilde{A}_1^{(i_1)}}(e_1^{'})\underline{\mu}_{\tilde{A}_2^{(i_2)}}(e_2^{'}) \tag{4}$$

$$\overline{\gamma}^{(i_1 i_2)} = \overline{\mu}_{\tilde{A}_1^{(i_1)}}(e_1^{'})\overline{\mu}_{\tilde{A}_2^{(i_2)}}(e_2^{'}) \tag{5}$$

The center-of-sets type reduction scheme (Mendel, 2001;Mendel & John, 2002) is to be used along with the defuzzification approach. The centroid of the type-2 output fuzzy set $\tilde{B}^{(i_1 i_2)}$ in (1) is represented by $C_{\tilde{B}^{(i_1 i_2)}}$, which is a type-1 interval fuzzy set $[c_l^{(i_1 i_2)}, c_r^{(i_1 i_2)}]$, i.e.,

$$C_{\tilde{B}^{(i_1 i_2)}} = \sum_{c \in [c_l^{(i_1 i_2)},\, c_r^{(i_1 i_2)}]} 1/c = [c_l^{(i_1 i_2)}, c_r^{(i_1 i_2)}] . \tag{6}$$

The type-reduced fuzzy output, denoted as b_{cos}, generated from the fuzzy controller in (1) is also an interval fuzzy set. Let $b_{cos} = [b_l, b_r]$. In order to calculate both b_l and b_r, assume that the DOF associated with $c_l^{(i_1 i_2)}$ is denoted as $\gamma_l^{(i_1 i_2)}$ and the DOF associated with $c_r^{(i_1 i_2)}$ is denoted as $\gamma_r^{(i_1 i_2)}$. Then,

$$b_l = \Big(\sum_{i_1=1}^{N_1}\sum_{i_2=1}^{N_2} \gamma_l^{(i_1 i_2)} c_l^{(i_1 i_2)}\Big) \Big/ \Big(\sum_{i_1=1}^{N_1}\sum_{i_2=1}^{N_2} \gamma_l^{(i_1 i_2)}\Big) , \tag{7}$$

and

$$b_r = \Big(\sum_{i_1=1}^{N_1}\sum_{i_2=1}^{N_2} \gamma_r^{(i_1 i_2)} c_r^{(i_1 i_2)}\Big) \Big/ \Big(\sum_{i_1=1}^{N_1}\sum_{i_2=1}^{N_2} \gamma_r^{(i_1 i_2)}\Big) . \tag{8}$$

Note that the DOF $\gamma_l^{(i_1 i_2)}$ and $\gamma_r^{(i_1 i_2)}$ in (7) and (8) are set as either $\underline{\gamma}^{(i_1 i_2)}$ or $\overline{\gamma}^{(i_1 i_2)}$ depending on the calculated values of b_l, b_r, and $c_l^{(i_1 i_2)}$ and $c_r^{(i_1 i_2)}$ in the following iterative computation process for b_l or b_r. The computation process for b_l is described as following.

1. Compute b_l in (7) by initially setting $\gamma_l^{(i_1 i_2)} = (\overline{\gamma}^{(i_1 i_2)} + \underline{\gamma}^{(i_1 i_2)})/2$, $i_1 = 1 \ldots N_1$, $i_2 = 1 \ldots N_2$. Let $b_l^{'} = b_l$.
2. Update b_l in (7) with $\gamma_l^{(i_1 i_2)} = \overline{\gamma}^{(i_1 i_2)}$ if $c_l^{(i_1 i_2)} \le b_l^{'}$ and $\gamma_l^{(i_1 i_2)} = \underline{\gamma}^{(i_1 i_2)}$ if $c_l^{(i_1 i_2)} > b_l^{'}$, $i_1 = 1 \ldots N_1$, $i_2 = 1 \ldots N_2$. Let $b_l^{''} = b_l$.
3. If $b_l^{''} \ne b_l^{'}$, go to step 4; otherwise stop and set $b_l = b_l^{''}$.
4. Set $b_l^{'} = b_l^{''}$ and return to step 2.

The value of b_r can be obtained by the process similar to the above except that both $\gamma_l^{(i_1 i_2)}$ and $c_l^{(i_1 i_2)}$ in the above computation process are replaced with $\gamma_r^{(i_1 i_2)}$ and $c_r^{(i_1 i_2)}$, respectively. In step 2 of the computation process for b_r, $\gamma_r^{(i_1 i_2)} = \underline{\gamma}^{(i_1 i_2)}$ if $c_r^{(i_1 i_2)} \le b_r^{'}$ and $\gamma_r^{(i_1 i_2)} = \overline{\gamma}^{(i_1 i_2)}$ if $c_r^{(i_1 i_2)} > b_r^{'}$, i_1 =

$1 \ldots N_1$, $i_2 = 1 \ldots N_2$. Different from the type reduction process proposed in (Mendel, 2001;Mendel & John, 2002), the values of $c_l^{(i_1 i_2)}$, $i_1 = 1 \ldots N_1$, $i_2 = 1 \ldots N_2$, need not be pre-arranged in an ascending order. The type-reduction scheme proposed in this paper directly uses $c_l^{(i_1 i_2)}$ to calculate $\gamma_l^{(i_1 i_2)}$ for every indices pair (i_1 i_2) rather than locating the order of $b_l^{'}$ in the ascending values of all $c_l^{(i_1 i_2)}$ before determining the value of $\gamma_l^{(i_1 i_2)}$. Therefore, the proposed modification of type-reduction scheme saves the computation effort compared to the one in (Mendel, 2001; Mendel & John, 2002).

After calculating both b_l and b_r in the type-reduced output b_{cos} of an interval singleton type-2 fuzzy controller based on (4)-(8) with $e_1(k) = e_1^{'}$ and $e_2(k) = e_2^{'}$, the defuzzified output

$$b(\mathrm{k}) \equiv \Delta\theta(k) = (b_l + b_r)/2. \tag{9}$$

4. Implementation of AGV's wall following control

It is shown in the above discussion that the wall following control of AGV mainly depends on delicate control of AGV's rotational increments. The implementation of AGV's rotational increments and the associated rotational dynamics will be further investigated in this section. The rotational dynamics of a nonholonomic AGV is shown in Fig. 2, where Q denotes the center of an AGV and Q' denotes the new position after AGV moving forward from Q for a period of sampling interval T. Let d_l and d_r be the moving distance of AGV's left and right wheel with respect to the Cartesian coordinate centered at the origin O. If r_l and r_r are the rotational radius for the left and right wheel, respectively, then,

$$d_l(k) = r_l \cdot \Delta\theta(k) = V_l(k) \cdot T \ , \tag{10}$$

$$d_r(k) = r_r \cdot \Delta\theta(k) = V_r(k) \cdot T \ . \tag{11}$$

where $V_l(\cdot)$and $V_r(\cdot)$ are AGV's left and right wheel speed, respectively. The speed of AGV can be defined as $V_{avg}(k) = (V_r(k) + V_l(\mathrm{k}))/2$. The moving distance $d_o(k)$ can be considered as the moving distance of AGV's center Q, i.e.,

$$d_o(k) = r \cdot \Delta\theta(k) = V_{avg}(k) \cdot T = (V_r(k) + V_l(k)) \cdot T \,/\, 2 \ . \tag{12}$$

From (11) and (12), the rotational increment for the *k-th* sampling interval

$$\Delta\theta(k) = (d_r(k) - d_l(k)) \,/\, (r_r - r_l) = (d_r(k) - d_l(k)) \,/\, 2w \ , \tag{13}$$

where w is the radius of AGV. Substituting $d_l(k)$ and $d_r(k)$ in (10) and (11) into (13),

$$\Delta\theta(k) = (V_r(k) - V_l(k))T \,/\, 2w \ . \tag{14}$$

Then,

$$V_r(k) - V_l(k) = 2w\Delta\theta(k) \,/\, T \ . \tag{15}$$

From (12),

$$V_r(k) + V_l(k) = 2d_o(k) \,/\, T \ . \tag{16}$$

Hence, $V_l(k)$ and $V_r(k)$ can be obtained from both (15) and (16) as following:

$$V_l(k) = (d_o(k) - w\Delta\theta(k)) / T \,, \tag{17}$$

$$V_r(k) = (d_o(k) + w\Delta\theta(k)) / T \,. \tag{18}$$

For wall following, AGV's average speed V_{avg} is set as a constant despite that the left and right wheel speed V_l and V_r vary with time. As long as V_{avg} is a constant, AGV's moving distance within every sampling interval, $d_o(k)$, is also a constant according to (12). Referring to (17) and (18), if $d_o(k)$ is set as a constant and $\Delta\theta(k)$ is determined by the type-2 fuzzy controller as in (9), $V_l(k)$ and $V_r(k)$ can be both determined. Since AGV's left and right wheel motor are driven by the voltage-controlled PWM drivers, the left and right wheel can be driven to achieve the calculated speed $V_l(k)$ and $V_r(k)$ by applying corresponding voltages to the PWM drivers.

Referring to Fig. 2 and (10)-(11),

$$r = (r_r + r_l) / 2 = (V_r(k) + V_l(k))T / 2\Delta\theta(k) \,. \tag{19}$$

Substituting (13) into (19) yields

$$r = (V_r(k) + V_l(k))w / (V_r(k) - V_l(k)) \,. \tag{20}$$

Referring to Fig. 2, assume that AGV's rotation angle is $\theta(k)$ at the *k-th* sampling interval with respect to x-axis of the global coordinate. Let $\Delta u(k)$ and $\Delta v(k)$ be AGV's displacement increment moving from Q to Q' with respect to the AGV's coordinate. Therefore,

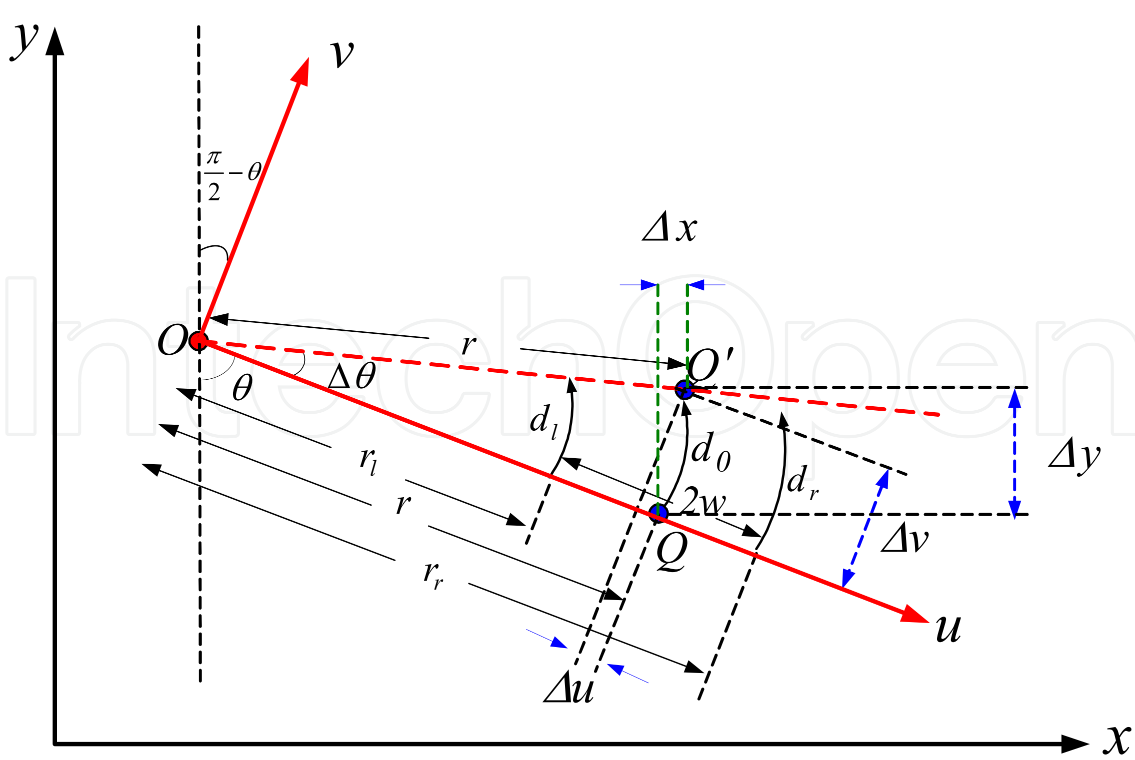


Fig. 2. Rotational dynamics of a holonomic AGV.

$$\Delta u(k) = r \cdot \cos(\Delta\theta(k)) - r \,, \tag{21}$$

and

$$\Delta v(k) = r \cdot \sin(\Delta\theta(k)) \,. \tag{22}$$

The *u-v* coordinate is the *x-y* global coordinate with clockwise rotation ($\pi/2$ - θ). Therefore,

$$\begin{bmatrix} \Delta x(k) \\ \Delta y(k) \end{bmatrix} = \begin{bmatrix} \cos(\frac{\pi}{2}-\theta) & \sin(\frac{\pi}{2}-\theta) \\ -\sin(\frac{\pi}{2}-\theta) & \cos(\frac{\pi}{2}-\theta) \end{bmatrix} \begin{bmatrix} \Delta u(k) \\ \Delta v(k) \end{bmatrix}. \tag{23}$$

Substituting (21) and (22) into (23),

$$\Delta x(k) = r(\sin(\theta(k)+\Delta\theta(k)) - \sin(\theta(k))) \,, \tag{24}$$

$$\Delta y(k) = r(\cos(\theta(k)) - \cos(\theta(k)+\Delta\theta(k))) \,. \tag{25}$$

With AGV's position and heading angle $[x(k), y(k), \theta(k)]^T$ at *Q*, the position and heading angle at *Q′* for the *(k+1)-th* sampling interval can be updated as

$$\begin{bmatrix} x(k+1) \\ y(k+1) \\ \theta(k+1) \end{bmatrix} = \begin{bmatrix} x(k) \\ y(k) \\ \theta(k) \end{bmatrix} + \begin{bmatrix} \Delta x(k) \\ \Delta y(k) \\ \Delta\theta(k) \end{bmatrix}, \tag{26}$$

where $\Delta x(k)$ and $\Delta y(k)$ are determined by (24) and (25), respectively, $\Delta\theta(k)$ is determined by the type-2 fuzzy controller as in (4)-(9).

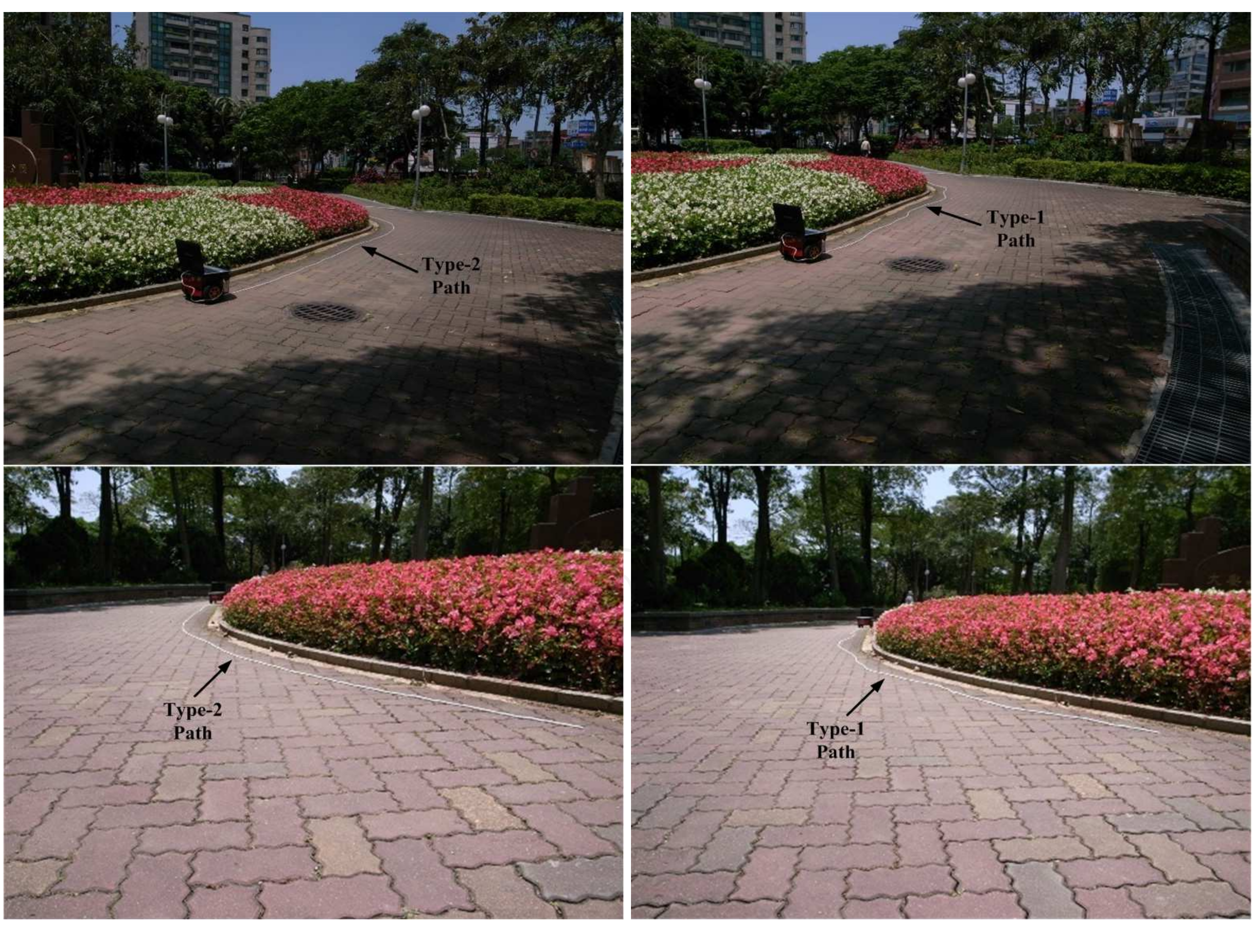
5. Experiment

The AGV is set to follow a round clump of bushes in the park as shown in Fig. 3. It is obvious that the ultra-sound signals transmitted from the sonar transceivers are easy to be deflected by the flowers, leaves and trigs in the bushes. The distance between the AGV and bushes measured by the sonar systems is contaminated by inevitable noise. Referring to (1), two different interval type-2 fuzzy sets are utilized for $\tilde{A}_1^{(i_1)}$ and $\tilde{A}_2^{(i_1)}$ describing the linguistic terms "negative" and "positive", respectively, i.e., N_1 = N_2 = 2. Let $[\underline{\mu}_{\tilde{A}_1^{(1)}}, \overline{\mu}_{\tilde{A}_1^{(1)}}] = [\underline{\mu}_{\tilde{A}_2^{(1)}}, \overline{\mu}_{\tilde{A}_2^{(1)}}]$ =[-35, -25], and $[\underline{\mu}_{\tilde{A}_1^{(2)}}, \overline{\mu}_{\tilde{A}_1^{(2)}}] = [\underline{\mu}_{\tilde{A}_2^{(2)}}, \overline{\mu}_{\tilde{A}_2^{(2)}}]$ =[25, 35]. Referring (6), a singleton is used to define the centroid of the output fuzzy set $\tilde{B}^{(i_1 i_2)}$ in (1). Let $c_l^{(1,1)} = c_r^{(1,1)}$ =-1.25, $c_l^{(1,2)} = c_r^{(1,2)}$ =-0.1, $c_l^{(2,1)} = c_r^{(2,1)}$ =0.1, $c_l^{(2,2)} = c_r^{(2,2)}$ =1.25. To verify the effectiveness and efficiency of the proposed type-2 fuzzy controller, the controller is compared with a type-1 fuzzy controller with similar parameterization. As in the type-2 fuzzy controller, 4 fuzzy rules are defined in the type-1 fuzzy controller. The parameterizations for the type-1 fuzzy controller are set to be as close to the type-2 settings as possible in order to have a fair comparison. The left and right semi-Gaussian function is defined as the membership function for the fuzzy sets describing the linguistic terms "negative" and "positive". Define the left and right semi-Gaussian function, respectively, as following.

$$LG(x;m_l,\sigma_l)=\begin{cases}1, & x\le m_l\\ \exp(-(x-m_l)^2/\sigma_l^2), & x>m_l\end{cases} \tag{27}$$

$$RG(x;m_r,\sigma_r)=\begin{cases}\exp(-(x-m_r)^2/\sigma_r^2), & x\le m_r\\ 1, & x>m_r\end{cases} \tag{28}$$

The left semi-Gaussian function with m_l = -30 and σ_l = 16.5 in (27) is used as the membership function of the fuzzy set describing the linguistic term "negative" for both e_1 and e_2. Similarly, the right semi-Gaussian function with m_r = 30 and σ_r = 16.5 in (28) is used as the membership function of the fuzzy set describing the linguistic term "positive" for both e_1 and e_2. The running paths of the wall-following results using type-2 and type-1 fuzzy controllers are compared in Fig. 3 (a) and (b). It is obvious that the running path due to the type-2 fuzzy controller is smoother than the one due to the type-1 fuzzy controller. The variations of AGV's rotation angle $\theta(k)$ in (26) with respect to time due to type-2 and type-1 fuzzy controller are compared in Fig. 4 (a) and (b). It numerically justifies that the running path due to the type-2 fuzzy controller is smoother because the variations of $\theta(k)$ in Fig. 4(a) due to the type-2 fuzzy controller is much smaller than the one in Fig. 4(b) due to the type-1 fuzzy controller.



(a) (b)

Fig. 3. Comparison of AGV's running paths due to (a) type-2 fuzzy controller, (b) type-1 fuzzy controller.

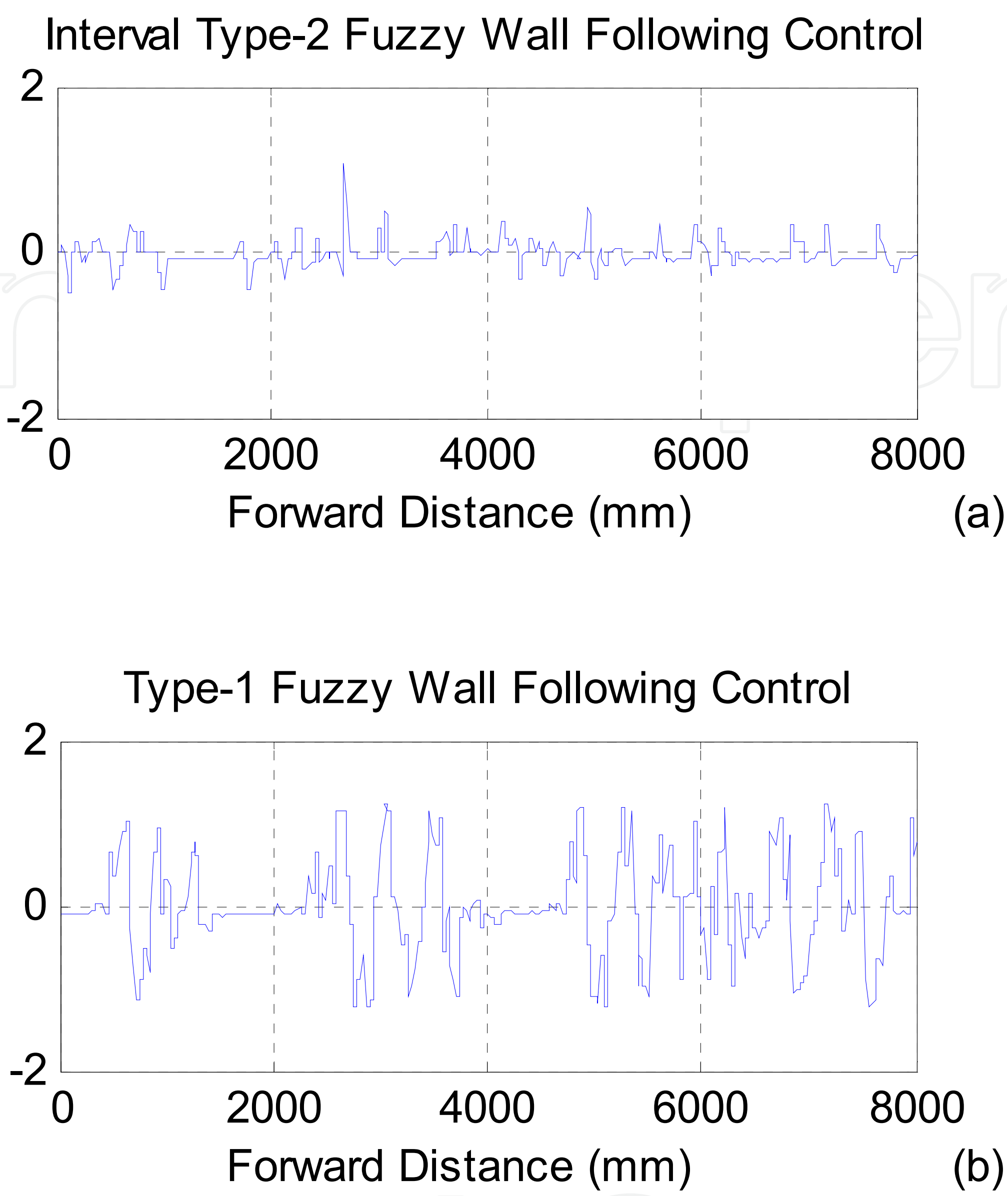


Fig. 4. Comparison of AGV's rotation angle $\theta(k)$ due to (a) type-2 fuzzy controller, (b) type-1 fuzzy controller.

6. Conclusion

A wall-following type-2 fuzzy controller for AGV has been designed in this paper. The proposed type-2 fuzzy controller is especially suitable for the AGV that uses sonar system to measure the distance between the AGV and the wall. The distance measuring scheme used in the sonar system is sensitive to the received ultra-sound signals. The proposed type-2 fuzzy controller features the robustness of the distance measurement. The inevitable noise problem in AGV's sonar-based distance measuring scheme is resolved by using type-2 fuzzy sets to define the distance measurements. Similar approach can also be applied to the sonar-based obstacle avoidance because the surface of obstacle might not be smooth enough to reflect the ultra-sound signals back to AGV's sonar transceivers.

7. References

[1] C.-F. Juang and C.-H. Hsu (2009). "Reinforcement ant optimized fuzzy controller for mobile-robot wall-following control," *IEEE Trans. Ind. Electron.,* vol. 56, no. 10, pp. 3931-3940, Oct. 2009.

[2] C. L. Hwang, L. J. Chang, and Y. S. Yu, "Network-based fuzzy decentralized sliding-mode control for car-like mobile robots," *IEEE Trans. Ind. Electron.,* vol. 54, no. 1, pp. 574-585, Feb. 2007.

[3] D. Wu, W. W. Tan (2005). "Computationally efficient type-reduction strategies for a type-2 fuzzy logic controller," in *Proc. IEEE Int. Conf. Fuzzy Systems,* pp. 353–358, 2005.

[4] H. A. Hagras (2004). "A hierarchical type-2 fuzzy logic control architecture for autonomous mobile robots," *IEEE Trans. Fuzzy Systems,* vol. 12, no. 4, pp. 524–538, Aug. 2004.

[5] H. Wu, J. Mendel (2002). "Uncertainty Bounds and Their Use in the Design of Interval Type-2 Fuzzy Logic Systems," *IEEE Trans. Fuzzy Systems,* vol. 10, no. 5, pp. 622–635, Oct. 2002.

[6] I. Baturone, F. J. Moreno-Velo, V. Blanco, and J. Ferruz (2008). "Design of embedded DSP-based fuzzy controller for autonomous mobile robots," *IEEE Trans. Ind. Electron.,* vol. 55, no. 2, pp. 928-936, Feb. 2008.

[7] J. Godjevac and N. Steele (1999). "Neuro-fuzzy control of a mobile robot," *Neurocomputing,* vol. 28, no. 1, pp. 127-143, Oct. 1999.

[8] J. M. Mendel and R. I. B. John (2002). "Type-2 fuzzy sets made simple," *IEEE Trans. Fuzzy Systems,* vol. 10, no. 2, pp. 117-127, April 2002.

[9] J. M. Mendel (2001). Uncertain Rule-Based Fuzzy Logic Systems: Introduction and New Directions, NJ: Prentice Hall PTR, 2001.

[10] K. C. Ng and M. M. Trivedi (1998). "A neuro-fuzzy controller for mobile robot navigatin and multirobot convoying," *IEEE Trans. Syst., Man, Cyern.-Pt. B: Cybern.,* vol. 28, no. 6, pp. 829-840, Dec. 1998.

[11] M. J. Er and C. Deng (2004). "Online tuning of fuzzy inference systems using dynamic fuzzy Q-learning," *IEEE Trans. Syst., Man, Cyern., Pt. B: Cybern.,* vol. 34, no. 3, pp. 1478-1489, Jun. 2004.

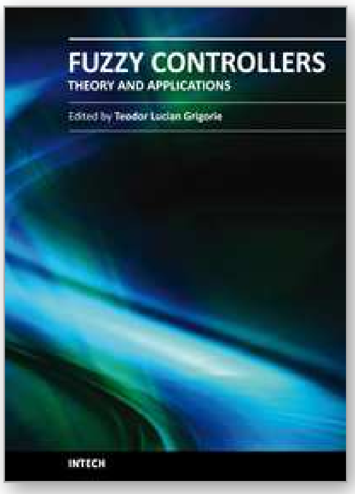
[12] N. N. Karnik and J. M. Mendel (2001). "Centroid of a type-2 fuzzy set," *Inform. Sci.,* vol. 132, no. 1-4, pp. 195–220, Feb. 2001.

[13] S. Nurmaini, S. Z. M. Hashim, and D. N. A. Jawawi (2009). "Environmental recognition using RAM-network based type-2 fuzzy neural network for navigation of mobile robot," in *Proc. Int. Conf. Computer and Automation Engineering,* 8-10 Mar., 2009, pp. 296-301

[14] T.-H. S. Li, S.-J. Chang, and Y.-X. Chen (2003). "Implementation of human-like driving skills by autonomous fuzzy behavior control on an FPGA-based car-like mobile robot," *IEEE Trans. Ind. Electron.,* vol. 50, no. 5, pp. 867-880, Oct. 2003.

[15] W. Tsui, M. S. Masmoudi, F. Karray, I. Song, and M. Masmoudi (2008). "Soft-computing-based embedded design of an intelligent wall/lane-following vehicle," *IEEE/ASME Trans. Mechatronics,* vol. 13, no. 1, pp. 125-135, Feb. 2008.

[16] Z. Liu, Y. Zhang, and Y. Wang (2007). "A type-2 fuzzy switching control system for biped robots," *IEEE Trans. Syst., Man, and Cybern.-Pt. C: App. and Rev.,* vol. 37, no. 6, pp. 1202–1213, Nov. 2007.



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Trying to meet the requirements in the field, present book treats different fuzzy control architectures both in terms of the theoretical design and in terms of comparative validation studies in various applications, numerically simulated or experimentally developed. Through the subject matter and through the inter and multidisciplinary content, this book is addressed mainly to the researchers, doctoral students and students interested in developing new applications of intelligent control, but also to the people who want to become familiar with the control concepts based on fuzzy techniques. Bibliographic resources used to perform the work includes books and articles of present interest in the field, published in prestigious journals and publishing houses, and websites dedicated to various applications of fuzzy control. Its structure and the presented studies include the book in the category of those who make a direct connection between theoretical developments and practical applications, thereby constituting a real support for the specialists in artificial intelligence, modelling and control fields.

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