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

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Abstract—Unexpected conditions are often encountered by practitioners in the navigation of autonomous guided vehicles (AGV). In dynamic circumstances, traditional fuzzy controller using simple type-1 fuzzy sets may not be robust enough to overcome uncertainties caused by noise-corrupted sonar signals. For this reason, an interval type-2 fuzzy wall-following controller (IT2FWFC) is developed to improve the resilience to inaccuracies that can hinder the normal operation of an AGV. The antecedent part of the proposed IT2FWFC is made up of type-2 fuzzy sets and its consequent part is formed from fuzzy singletons. Furthermore, the non-sensitiveness property of the IT2FWFC for noise-elimination is also analyzed in this paper. In order to reduce computational loads during practical control, a simplified center-of-sets (COS) type-reduction procedure with clearly marked rule indices is also developed. Experiment results are included to illustrate the robustness of an AGV when detecting objects with uneven surfaces and exhibiting its wall-following behavior at the same time. The wall-following behavior of the IT2FWFC outperforms that of the type-1 fuzzy wall-following controller (T1FWFC) designed previously by the same framework of this paper.

Keywords: Noise-Elimination, Wall-Following Behavior, Interval Type-2 Fuzzy Logic Control, Simplified Type-Reduction Procedure, Autonomous Guided Vehicle.

I. INTRODUCTION

For autonomous guided vehicles (AGV) navigating in changing and unstructured environments, the use of sonar sensors is a big help. But sonar detected signals are not always immune to noise sources coming from the respective environments or mechanical drawback itself. For carrying out the wall-following behavior, the obstacles dealt with are usually made of different materials and their surface structures uneven. For instance, the irregular edge of a flowerbed is one such example; the reflected sonar signals from such an obstacle can produce even more inaccuracies. That is why the selection of a suitable controller is essential to the handling of uncertainties required for the completion of the task. Other factors that can influence the outcome of completing the task are: (1) it is not always possible to construct accurate mathematical representation for an AGV, (2) it is difficult to estimate a fixed pattern of complex dynamics, and (3) not all environmental disturbances are predictable. Fuzzy control technique using linguistic control rules and human experiences might be a good alternative to employ [1-5].

Although fuzzy logic controllers are credited with a high degree of reliability for controlling a complicated system (the AGV), the type-1 fuzzy control is a technique using simple fuzzy sets that may not be robust enough to overcome uncertainties from noise-corrupted sonar signals. The type-1 membership functions can not expect to show accuracy for anticipating unexpected event. It is hard to predict what type of problem may occur next. To translate this degree of uncertainty into linguistic rules beforehand so that the corresponding fuzzy rule-based can always contain the uncertain element as part of its whole set of linguistic variables is an impossible mission [6-8].

Therefore, a lot of investigations have focused on improving type-2 fuzzy logic control for better handling of uncertainties and nonlinear systems. In [9] and [10], the type-2 fuzzy control with a hierarchical structure was used by Hagras to implement real-time operation for autonomous mobile robots (AMR) navigating in new environments. In [11], Liu, Zhang, and Wang designed a type-2 fuzzy switching control system to control the periodic walking motion of a biped robot. In [12], the type-2 fuzzy-neural network was adopted by Nurmaini, Hashim, and Jawawi to control the navigation of an AMR. In all these cases, sophisticated robots were being developed to improve object detection capability. The other purpose was to set the stage for type-2 fuzzy-neural network to be implemented on a simple microprocessor platform. To reduce heavy computational loads of typical type-reduction processes, an efficient type-reduction strategy was presented by Wu and Tan as in [13]. Other concepts equivalent to type-1 fuzzy sets can combine with new mathematical interpretations of the Karnik-Mendel (KM) iterative procedure to reduce computational loads of type-reduction processes [14].

In order to reduce the amount of time consuming computations, an interval type-2 fuzzy wall-following controller (IT2FWFC) with a simplified center-of-sets (COS) type-reduction procedure is developed in this paper. The new design is an extension of the type-1 fuzzy wall-following controller (T1FWFC) because the distribution of parameters of the previously designed controller is suitably expanded to cater to more uncertainties. This procedure enhances the wall-following capability of the AGV. It can closely follow a planned path or keep a required distance from all types of objects with uneven surfaces. Furthermore, the noise-elimination feature of the IT2FWFC is also analyzed later on in this paper. From the analysis, it will be
shown that the IT2FWFC designed with type-2 Gaussian functions is more robust when noise-corrupted sonar signals are to be handled.

II. INTERVAL TYPE-2 FUZZY LOGIC CONTROL

A. Type-2 Fuzzy Logic Controller (T2FLC)

A type-2 fuzzy set

\[
\tilde{A} = \int_{\mathbb{X}} \mu_{\tilde{x}}(x)/x = \int_{\mathbb{X}} \left[ \int_{\mathbb{X}} f_i(u)/u \right] / x, \quad J_i \subseteq [0,1]
\]  

(1)

in the universe of discourse is characterized by a membership function \( \mu_{\tilde{x}}(x) \) which can be referred as a secondary set [6][7], where \( \mu_{\tilde{x}}(x), x \in X \) is a type-1 fuzzy set in the range of \([0,1]\). The amplitude of a secondary membership function, \( f_i(u) \), is called a secondary grade, i.e. \( 0 \leq f_i(u) \leq 1 \). The uncertainty in the primary membership function of \( \tilde{A} \) is a bounded region called the footprint of uncertainty (FOU), and the FOU is bounded by a lower membership function \( \mu_l(x) \) and an upper membership function \( \mu_u(x) \). For reducing the complication of the general type-2 fuzzy logic control, if \( f_i(u) \) is to be equal to one, then the interval type-2 fuzzy set can be expressed as

\[
\tilde{A} = \int_{\mathbb{X}} \mu_{\tilde{x}}(x)/x = \int_{\mathbb{X}} \left[ \int_{\mathbb{X}} \mu_l(x, \pi_i) \right] / x
\]  

(2)

where \( J_i \) is a set of the primary membership value of \( x \) for \( \forall x \in X \). Consider a multiple-input-single-output (MISO) interval type-2 fuzzy control system which has \( n \) dimensional inputs \( x_1, \ldots, x_n \in X_i \) and an output \( y \in Y \), each fuzzy rule can be expressed as \( Rule_{(\tilde{A}^i) \times (\tilde{A})} \rightarrow \tilde{A} \rightarrow \tilde{A} \) with the indices, \( i_1 = 1 \sim q_1, \ldots, i_n = 1 \sim q_n \), where \( \tilde{A} \) is an interval fuzzy set. Since the singleton fuzzification and \textit{Meet} inference operator are considered, the interval degree of firing (DOF) set can be expressed as

\[
\tilde{f}^{(1 \sim q_1 \sim \sim 1 \sim q_n)}(x') = \tilde{f}^{(1 \sim q_1 \sim \sim 1 \sim q_n)}(x')
\]

\[
\tilde{f}^{(1 \sim q_1 \sim \sim 1 \sim q_n)}(x') = \frac{\mu_l(x', \pi_i)}{\mu_l(x', \pi_i)}
\]

\[
\tilde{f}^{(1 \sim q_1 \sim \sim 1 \sim q_n)}(x') = \frac{\mu_l(x', \pi_i)}{\mu_l(x', \pi_i)}
\]

(3)

are taken as the lower and the upper firing sets with the fuzzy intersection operation \( \ast \).

B. Simplified Type-Reduction Procedure

The type-reduction mechanism was proposed by Karnik and Mendel (KM) in [6][8] to derive the crisp outputs of the type-2 fuzzy logic controllers. Since the typical COS type-reduction approach in [6][8][9] does not have clear enough rules, leading to the most time consuming step when the left index \( L \) and the right index \( R \) are to be found. For this reason, a simplified COS type-reduction procedure is presented in this section. The left-most output \( y_l \) and the right-most output \( y_r \) can be obtained by the interval fuzzy singletons \( \tilde{A}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} = \tilde{A}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \), where \( \tilde{A}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} = \tilde{A}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \) and \( \tilde{A}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} = \tilde{A}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \). The interval set of the DOF is defined as \( \tilde{f}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} = \tilde{f}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \), where \( \tilde{f}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \) which is an interval during the lowest and the highest grade is denoted as the firing strength of the \( (i_1, i_2, \ldots, i_n) \) fuzzy rule. For any \( y \in Y = [y_l, y_r] \), the two most outputs can be expressed as

\[
y_l = \frac{\sum_{i=1}^{q_1} \sum_{j=1}^{q_2} \ldots \sum_{k=1}^{q_n} f_j^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \tilde{A}^{(1 \sim q_1 \sim \sim 1 \sim q_n)}(x_{l_{i,j,k}})}{\sum_{i=1}^{q_1} \sum_{j=1}^{q_2} \ldots \sum_{k=1}^{q_n} f_j^{(1 \sim q_1 \sim \sim 1 \sim q_n)}(x_{l_{i,j,k}})}
\]

(4)

and

\[
y_r = \frac{\sum_{i=1}^{q_1} \sum_{j=1}^{q_2} \ldots \sum_{k=1}^{q_n} f_j^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \tilde{A}^{(1 \sim q_1 \sim \sim 1 \sim q_n)}(x_{r_{i,j,k}})}{\sum_{i=1}^{q_1} \sum_{j=1}^{q_2} \ldots \sum_{k=1}^{q_n} f_j^{(1 \sim q_1 \sim \sim 1 \sim q_n)}(x_{r_{i,j,k}})}
\]

(5)

The values of \( \tilde{A}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \) and \( \tilde{f}^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \) that are associated with \( y_l \) and \( y_r \) are denoted as \( \tilde{A}^{(i_1 \sim q_1 \sim \sim i_n \sim q_n)} \), \( \tilde{A}^{(i_1 \sim q_1 \sim \sim i_n \sim q_n)} \), and \( \tilde{A}^{(i_1 \sim q_1 \sim \sim i_n \sim q_n)} \). For calculating \( y_r \), the simplified COS type-reduction procedure is illustrated as follows:

**Procedure 1.** Calculate the left-most output \( y_l \).

1. **(FL1)** Compute \( y_l \) in Eq. 4 by initially setting \( f_j^{(1 \sim q_1 \sim \sim 1 \sim q_n)}(x_{l_{i,j,k}}) = \frac{(1 - q_1) + (1 - q_2) + \ldots + (1 - q_n)}{2} \) for \( i_1 = 1 \sim q_1, i_2 = 1 \sim q_1, \ldots \), and \( i_n = 1 \sim q_n \). where \( f_j^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \) and \( f_j^{(1 \sim q_1 \sim \sim 1 \sim q_n)} \) are pre-computed by Eq. 3, and let \( y_l' = y_l \).

2. **(FL2)** Compute \( y_l' \) in Eq. 4 with \( f_j^{(1 \sim q_1 \sim \sim 1 \sim q_n)} = f_j^{(1 \sim q_1 \sim \sim 1 \sim q_n)}(x_{l_{i,j,k}}) \), if \( \tilde{A}^{(i_1 \sim q_1 \sim \sim i_n \sim q_n)} \leq y_l' \), and let \( y_l' = y_l \).

3. **(FL3)** Compare \( y_l' \) and \( y_r' \), if \( y_l' = y_r' \), then go to (FL4). If \( y_l' = y_r' \), then stop and set \( y_r = y_l = y_r' \).

4. **(FL4)** Set \( y_l = y_l' = y_r' \), and return to (FL2).
simplified procedures and the rule indexing (i) of typical COS type-reduction [9][10] can be replaced by \( (i_1, i_2, \ldots, i_n) \). By the properties above, it is known that \( y_i' \) and \( y_i'' \) of every procedures are very important to separate the lower firing strengths \( f_i^{(1)}(y_i') \) and the upper firing strengths \( f_i^{(2)}(y_i'') \). Hence, the left index \( L \) and the right index \( R \) are not necessary involved in the simplified procedures. And the outputs \( y_i' \) and \( y_i'' \) can be calculated directly by Eq. 4 and Eq. 5 with the following conditions:

\[
\begin{align*}
\{ f_i^{(1)}(y_i') \} & = f_i^{(1)}(y_i') \quad \text{if} \quad \omega_i^{(1)}(y_i') \leq y_i', \\
\{ f_i^{(2)}(y_i'') \} & = f_i^{(2)}(y_i'') \quad \text{if} \quad y_i' < \omega_i^{(2)}(y_i'') \\
\{ f_i^{(1)}(y_i') \} & = f_i^{(1)}(y_i') \quad \text{if} \quad \omega_i^{(1)}(y_i') < y_i', \\
\{ f_i^{(2)}(y_i'') \} & = f_i^{(2)}(y_i'') \quad \text{if} \quad y_i'' \leq \omega_i^{(2)}(y_i'') \quad \tag{6}
\end{align*}
\]

After the two most outputs, \( y_i \) and \( y_i' \), are determined, the complete control actions can be obtained by \( Y_{Y^{2}FWFC} = (y_i + y_i')/2 \). Note that the suffix \( f \) of \( y_i \) and \( y_i' \) shown in step 3 denote the final values of \( y_i' \) and \( y_i'' \). By the ascending-order processes, the left index \( L \) and the right index \( R \) are discarded in the simplified procedures resulting in the massive reduction of computational loads.

### III. INTERVAL TYPE-2 FUZZY WALL-FOLLOWING CONTROL

For any AGVs, wall-following behavior is characterized by the maneuvering along the sides of unexpected objects while keeping a required distance from the objects. The objects usually are made of different materials and the materials can have uneven surface textures. It has been found that the varieties of materials and non-uniform textures are causing sonar sensors deployed to receive error signals while measurements are taken. For example, enough robustness and non-sensitiveness were lacking when T1FWFC with simple type-1 membership functions was used to maintain various control accuracies. Hence, an IT2FWFC is necessary for overcoming unexpected variances caused by noise-corrupted signals. Sonar signals that are fed into the IT2FWFC are error signals, \( e_i \) and \( e_i' \), that are taken as its input variables.

For the example 10-3 [6], the antecedent fuzzy sets are defined with type-1 Gaussian functions and the consequent sets are represented by interval type-2 Gaussian functions. This type of membership functions is ideal for the purpose of improving the response and sensitivity to noise-corrupted input signals when measurements are taken. Nevertheless, since noise-elimination is important for wall-following behavior, the antecedent type-2 fuzzy sets and the consequent fuzzy singletons for the IT2FWFC have been designed (see the solid lines in Fig. 1). For the T1FWFC, the input variables for fuzzification are partitioned into two fuzzy sets and the output variables are partitioned into four sets of fuzzy singleton defuzzifiers. The membership functions of the antecedent fuzzy sets and the fuzzy singletons of the consequent sets are shown in Fig. 1 (see the medium dotted lines in (a, b) and the solid lines in (c)).

In order to compare separately the required performance of the IT2FWFC and the T1FWFC, the left fuzzy singleton \( \omega_1^{(1)} \) and the right fuzzy singleton \( \omega_1^{(2)} \) of the IT2FWFC are defined to be equal to the fuzzy singleton \( \omega_1^{(1)} \) of the T1FWFC. Based on the type-1 fuzzy membership functions of T1FWFC, the interval type-2 membership functions can be suitably expanded to present a wider distribution curve for the various sonar characteristics. The data collected from the different objects will be coming from a wider distribution, i.e., to give a more accurate picture of the actual standard deviations and means of the data collected by the T1FWFC. Since there might have situations where the consequent fuzzy sets of the different fuzzy rules are in the same category, the fuzzy singletons of the T1FWFC and IT2FWFC are defined as \( \omega_1^{(1)} = \omega_1^{(2)} = \omega_1^{(n)} \in W^{(n, n)} = \{ \omega_1, \omega_2, \omega_3, \omega_4 \} \) with \( \omega_1 = -\omega_1 \). After the simplified COS type-reduction processes are completed, the complete control actions of the IT2FWFC can be determined by the average of Eq. 4 and Eq. 5 with \( i_1, i_2 = 1 \sim 2 \).

![Figure 1. Membership functions.](image)

### IV. ANALYSIS FOR THE NON-SENSITIVE PROPERTY OF THE IT2FWFC

For the T1FWFC, its control action is determined as in

\[
Y_{T1FWFC} = \frac{f^{(1,1)} \omega^{(1,1)} + f^{(1,2)} \omega^{(1,2)} + f^{(2,1)} \omega^{(2,1)} + f^{(2,2)} \omega^{(2,2)}}{f^{(1,1)} + f^{(1,2)} + f^{(2,1)} + f^{(2,2)}}
\]

\[
= \frac{(f^{(2,2)} - f^{(1,1)}) \omega^{(2,2)} + (f^{(2,1)} - f^{(1,2)}) \omega^{(2,1)}}{f^{(1,1)} + f^{(1,2)} + f^{(2,1)} + f^{(2,2)}} \quad \tag{7}
\]
In order to calculate the control actions of the IT2FWFC, there are five conditions that are associated with the simplified COS type-reduction procedures.

\[
\begin{align*}
\text{condition 1: } & (\omega_1 \leq y_y < \omega_2) \text{ and } (\omega_3 < y_y \leq \omega_4) \\
\text{condition 2: } & (\omega_1 < y_y < \omega_2) \text{ and } (\omega_3 < y_y \leq \omega_4) \\
\text{condition 3: } & (\omega_2 \leq y_y < \omega_3) \text{ and } (\omega_3 < y_y \leq \omega_4) \\
\text{condition 4: } & (\omega_1 < y_y < \omega_2) \text{ and } (\omega_3 < y_y < \omega_4) \\
\text{condition 5: } & (\omega_1 < y_y < \omega_2) \text{ and } (\omega_3 < y_y < \omega_4)
\end{align*}
\]

For condition 1, the type-2 control action is

\[
Y_{IT2FWFC} = \frac{\left[ f_i^{(1,1)} \omega^{(1,1)}_1 + f_{i1}^{(1,2)} \omega^{(1,2)}_1 + f_{i2}^{(1,2)} \omega^{(2,2)}_2 \right] \\ \times \left[ f_i^{(1,1)} + f_{i1}^{(1,2)} + f_{i2}^{(2,2)} + f_{i3}^{(2,2)} ight]}{\left[ 2 \left( f_i^{(1,1)} + f_{i1}^{(1,2)} + f_{i2}^{(2,2)} + f_{i3}^{(2,2)} \right) \right] \\ \times \left[ f_i^{(1,1)} + f_{i1}^{(1,2)} + f_{i2}^{(2,2)} + f_{i3}^{(2,2)} \right]} = 0
\] (10)

From Eq. 7 and Eq. 10, it can be seen that \( Y_{IT2FWFC} \) is much less than \( Y_{T1FWFC} \), and so on for the other conditions. Therefore, the sensitiveness of the IT2FWFC is much less than the T1FWFC.

\[ m = \frac{1}{N} \sum_{i=1}^{N} z_i \quad \text{and} \quad \sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (z_i - \mu)^2} \] (11)

where \( z_i \) is the actual measured values of fixed distances and \( N \) is the total number of measured data.

Since non-sensitiveness is essential for the AGV to perform wall-following behaviors when navigating with high precision at a desired distance from a row of wall, the average size of the shifted means and the maximum distribution of the standard deviations are used to determine the parameters of the IT2FWFC. For comparing the performances between the T1FWFC and the IT2FWFC, the parameters of the T1FWFC are firstly decided as follows. The means of the semi-Gaussian membership functions are defined as \( [m_0^i, m_0^j]=[m_0^i, m_0^j]=-30 \ 30 \) , and the standard deviations are suitably chosen as \( [\sigma_0^i, \sigma_0^j]=[\sigma_0^i, \sigma_0^j]=\{16.5 \ 16.5 \} \). The fuzzy singletons are assigned as \( [\omega_1, \omega_2, \omega_3] \) = \{\text{1.25, 0.1, 0.1, 1.25}\}. For the characteristics of the sonar sensors, the unknown means of the interval type-2 semi-Gaussian functions are shifted by the average mean values as shown in Table I. There are \( [m_0^i, m_0^j, m_0^j]=[m_0^i, m_0^j, m_0^j]=-35 \ 25 \ 25 \ 25 \ 35 \). From the output analysis in section 4, it is known that non-sensitiveness is greatly affected by lower values of DOF. Hence, the standard deviations are spread out as \( \{\sigma_0^i, \sigma_0^j, \sigma_0^j, \sigma_0^j\}=[6 \ 27 \ 27 \ 6] \). Moreover, the consequent fuzzy singletons of the IT2FWFC and the T1FWFC are defined with the same values.

The experimental results from the wall-following behavior of the AGV around a garden which has many clumps using the designed IT2FWFC and T1FWFC are provided in Fig. 2 to Fig. 4. Fig. 2 shows a non-sensitiveness region with \( |Y_{IT2FWFC}|<|Y_{T1FWFC}|\times 10^{-7} \).
In Fig. 3, each of the four pictures shows a circular path that the AGV made as it completes the task of keeping a fixed distance while making curves along the side of a flowerbed located in a garden. The pictures also show that the IT2FWFC outperforms the T1FWFC in terms of robustness and adaptation to environment judging from the curvature of the path taken. The location of experiment is purposely chosen so that the site is saddled with objects made of different materials and with uneven surface textures. Since smaller values translate into finer control actions, the values that represent the control actions of the IT2FWFC in Fig. 4(a) are smaller than the control actions of the T1FWFC in Fig. 4(b).

VI. CONCLUSIONS

For the wall-following behavior of autonomous guided vehicles (AGV), the objects usually are made of different materials that come with uneven structures. External disturbances also play a part in causing the sonar sensors to produce measurement errors. An interval type-2 fuzzy wall-following controller (IT2FWFC) which has type-2 fuzzy sets of the antecedent part and the fuzzy singletons in the consequent set is being developed to minimize inaccuracies. In order to compare the robustness between the traditional type-1 fuzzy control approach and the proposed type-2 fuzzy control system, the parameters of the IT2FWFC are defined by suitably expanding the distribution of parameters of the type-1 fuzzy wall-following controller (T1FWFC).

With the simplified center-of-sets (COS) type-reduction procedure, computational loads and time consumption can be reduced. This is because the ascending-order processes, the left index $L$, and the right index $R$ that belong to the typical COS type-reduction approach are omitted in this paper.
The results of the experiments are included to indicate that the non-sensitiveness and the robustness of the proposed design of the IT2FWFC outperform that of the T1FWFC. From the clump following experiment, it proves that the designed IT2FWFC can meet the required noise-elimination and robustness expectation.

REFERENCES


TABLE I.  SONAR SIGNAL DATA BASE FOR DIFFERENT ENVIRONMENT MEASUREMENTS

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