ANFIS-Based Navigation for HVAC Service Robot with Image Processing

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Abstract. In this paper, we present an ongoing work on the autonomous navigation of a mobile service robot for Heat, Ventilation and Air Condition (HVAC) ducting. CCD camera mounted on the front-end of our robot is used to analyze the ducts openings (blob analysis) in order to differentiate them from other landmarks (blower fan, air outlets and etc). Distance between the robot and duct openings is measured using ultrasonic sensor. Controller chosen is ANFIS where its architecture accepts three inputs; recognition of duct openings, robot positions and distance while the outputs is maneuver direction (left or right). 45 membership functions are created from which produces 46 training epochs. In order to demonstrate the functionality of the system, a working prototype is developed and tested inside HVAC ducting in ROBOCON Lab, IIUM.

1. Introduction
Recent robot navigations systems are focusing more on operating in a dynamic and complex environmental situation. Presently, ANFIS approach is becoming one of the major areas of interest since the combination of fuzzy logic and neural network will remove individual disadvantages and combines the both features for robust and excellent control but remains relatively easy [1-3]. More traditional methods require extensive mathematical analysis. However, in most unstructured, real-life scenarios, adequate mathematical modeling is almost impossible to derive, but nevertheless, robots are still required to perform in these conditions [4]. Hence, fuzzy logic and neural network are good solutions, where fuzzy logic can be used as a controller while concurrently, the neural network part will acts as a ‘self-learner’ and ‘self-tuner’ so that it controls the behavior of fuzzy logic controller autonomously [5].¹

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Meanwhile, the implementation of visual analysis will provide robustness of application to the robot; the system could later be enhanced to analyze the quality of cleaning done inside the ducts, improve navigation by implementing more sophisticated algorithm or to simply eliminate the need for distance sensor by implementing perception of depth analysis. Our initial phase of visual analysis will focuses on landmark recognition to navigate the robot successfully in HVAC ducting. There are plenty of methods for recognizing landmarks such as sonar sensor, IR sensor and others, but, the frequent use of illuminator and camera for ducting, in-pipe and sewage robots prompt for image-based algorithm for convenience and efficiency [6].

1.1. HVAC service robot

HVAC service robot developed is a prototype comprises of two primary systems, 1) robotic system (a robotic body comprises of mechanical, electronic and circuitry) and 2) monitoring and control system (system is build inside a briefcase). Full system is shown is Figure 1

![Figure 1: HVAC service robot (complete system)](image)

In brief, the robotic system is a mobile robotic base attached with an ultrasonic sensor and a CCD camera. Visual output from the camera is then displayed on the monitoring system. An operator is assigned to control all the equipment on board (robotic arm and cleaning brush) while at the same time maneuver the robot inside HVAC ducting. In this paper, a small part of the system (i.e. robot maneuver) which initially is tele-operated is then upgraded into autonomous by applying ANFIS. Table 1 below shows the general specification of the robot.

| Item/Criteria | Specification | Description |
|---------------|---------------|-------------|
| Overall dimension | 300 mm (l) by 185 mm (b) by 305 mm (h) | General specification of the robot |
| Kerb Weight            | 2.10 kg          | -The estimated maximum possible mass is still assumed here -Without considering additional arm manipulator and payload. |
|----------------------|------------------|-------------------------------------------------------------------------------------------------------------------|
| Velocity             | 0.500 m/s        |                                                                                                                  |
| Additional payload   | 3.5 kg           |                                                                                                                  |
| Type of control      | Tele-operated    | range about 30 meters, could be upgraded to 100 meter                                                          |
|                      | (upgraded into autonomous) |                                                                                                                 |
| Power source         | 2 Lithium Polymer batteries, 3500 miliampere hour, 11volt. |                                                                                                                  |
| Camera               | CCD camera,      | 9 volt battery is needed for power                                                                                   |
|                      | Output- PLA/CCIR NTSC/EIA, Resolution-380 TV tines, Scan frequency: PLA/CCIR: 50 Hz NTSC/EIA:60 Hz |                                                                                                                  |
| Monitor              | LCD 5 inch       |                                                                                                                  |
| Brush                | 0.2 HP/Speed control/Reverse driving control | Actuator is a brushless DC motor with ESC for speed control                                                      |
| Joystick             | Sony PS2(modified) |                                                                                                                  |
| Standard working distance | 30 meter         | Total length of the cable is 40 meter                                                                              |
| BALUN                | A type of electrical transformer | Eliminate long distance video problem. Maximum 100meter                                                             |
| AV +data cable       | Modified CAT5 cable |                                                                                                                  |
| Ultrasonic sensor    | Parallax ultrasonic distance sensor | Precise for distance within 2 cm to 3 m range                                                                       |
2. Methodology
First part of the process is image processing. Image input from CCD camera is send to PC through tether. Images are later analyzed by MATLAB, where image pre-processing and blob analysis is used to analyze and acquire crucial information before relaying the result into second part. Second part is ANFIS controller for HVAC robot navigation. This part involves with taking all the information from first part and combines with data from ultrasonic sensor before determines the appropriate output. In this paper, variable output of our interest is ‘maneuver angle’

2.1 Image processing
The objective of image processing being implemented is to detect, recognize and analyze HVAC ducting openings. The properties of the openings such as the shapes, centre position (centroid) and perimeter extracted are valuable information in order to facilitate our image analysis. Data collected from various sample images are recorded to create a data set where training data set and checking data set for our ANFIS are derived from. Figure 2 below shows the overall procedure carried-out to obtain the data set. The procedure comprises of 2 distinct parts; pre-processing (stage 1, stage 2 and stage 3) and feature extraction (stage 4 and stage 5)

Figure 2: Procedure for duct opening’s detection

Original image obtained from CCD camera is a mixture of noises and useful data. This can cause many unnecessary additional calculations and reduces image processing efficiency. Hence, pre-processing stage is introduced. Pre-processing stages are, 1) conversion of data classes and image types (RGB to Grayscale), 2) binarization of image and 3) thresholding to omit small objects for clearer image. These stages are then followed by feature extraction stages (stage 4 and 5) where isolation of certain aspects of the image is done with the objective of finding line and shapes before statistical analysis is performed. Lastly, simple calculation is applied to determine the shape of the object.

2.1.1 Pre-processing
In order to reduce image complexity, color image from our CCD camera is changed into intensity image (grayscale). This step is crucial in order to facilitate boundary tracing and blob analysis, while emitting the parameters of non-interest (color, texture and etc). The resultant grayscale image, even though reasonably efficient in storage space (1 byte for each pixel), must be changed from ‘uint8’ type to ‘double’ in order to permit arithmetic operation on it. Next step involves binarization and thresholding. In binarization, a gray level \( T = 100 \) is chosen to separate every pixel to 2 different states; black or white.

A pixel becomes \{ 
white if its gray level is \( > 100 \) 
black if its gray level is \( \leq 100 \) 
}
Since the resultant binary image contains unwanted pixels, second ‘thresholding’ operation is carried-out. This time, instead of grey level, we used pixel values to remove pixels which don’t belong to the region of interest. All objects contain fewer than 300 pixels are removed. Pre-processing procedure results are shown in Figure 3.

![Figure 3: (a) Original, (b) Grayscale, (c) Binary, (d) Small objects removed](image)

2.1.2 Feature extraction
Ideal images gained after pre-processing stages are fit for statistical analysis where features of duct openings are extracted. Opening’s statistical information such as area, perimeter and centroid can be extracted from ROI using a method called blob analysis. A blob (binary large image) is an area of touching pixels with the same logical state. Hence, all related pixels are being grouped accordingly, which later translated into meaningful black and white regions Matlab can easily produce centroid location, area and perimeter using blob analysis system objects. Final step is where circularity is calculated which depends on information gathered in blob analysis earlier. This information is fed into equation (1) to form a metric indicating the roundness of the object.

\[
circularity = \frac{\text{perimeter}^2}{4 \times \pi \times \text{area}}
\]  

(1)

Through rigorous tests, it is established that, for our case, the thresholds are as recorded in Table 2.

| Circularitiy threshold | Types of opening |
|------------------------|------------------|
| < 1.19                 | circle           |
| < 1.53                 | square           |
| > 1.53                 | other shapes     |
2.2 **ANFIS controller for robot navigation**

ANFIS is a fuzzy inference system implemented in the framework of adaptive networks. By using a hybrid learning procedure, the proposed ANFIS can construct an input-output mapping based on both human knowledge (in the form of fuzzy if-then rules) and stipulated input-output data pairs [7]. In other words, ANFIS is a fuzzy inference system employing fuzzy IF-THEN rules can model the qualitative aspects of human knowledge and reasoning processes without employing precise quantitative analyses. Fuzzy control is by far the most successful applications of the fuzzy set theory and fuzzy inference systems [9]. Due to the adaptive capability of ANFIS, its applications to adaptive control and learning control are immediate. Most of all, it can replace almost any neural networks in control systems to serve the same purposes. Rather selecting the data, randomly, the initial weights obtain from desire data. Therefore more learning speed and more convergence should be assured. This fact is the most advantage of ANFIS [7].

The ANFIS analyzed here is a first order Takagi Sugeno Fuzzy Model [8], [7], [10]. In current analysis, there are three inputs: Duct opening (x1), robot position (x2), and distance (x3) while the output is Steering angle. The if-then rules for the ANFIS architecture are defined as follows:

**Rule:** \( \text{IF } x_1 \text{ is } A_j; x_2 \text{ is } B_k; x_3 \text{ is } C_m \)  
**THEN** \( F_i = p_i x_1 + r_i x_2 + s_i x_3 \)

Where  
\( F_i = p_i x_1 + r_i x_2 + s_i x_3 + u_i \) for steering angle  
\( J=1 \text{ to } 3; k=4 \text{ to } 8; m=9 \text{ to } 11; \text{ and } i=1 \text{ to } 45 \)

A, B and C are the fuzzy membership sets defined for the input variables x1, x2, x3 and J,K and M are the number of member ship functions for the fuzzy systems of the inputs x1, x2, x3 and x4 respectively. Fi is the linear consequent functions defined in terms of the inputs (x1, x2, and x3) . qi,ri, si . and ui are the consequent parameters of the ANFIS fuzzy model. In the ANFIS model, nodes of the same layer have similar functions. The output signals from the nodes of the previous layer are the input signals for the current layer. Since restriction on ANFIS is applied, none of the rules could share the same output membership function, thus the number of rules equal to the number of output membership functions. In this case, the number is fixed to 45.

Overall ANFIS system can be visualized in Figure 4. In order to make the system easier to understand, ANFIS system in Figure 4 must be cross-referenced to its FIS part (Figure 5), before further explanation takes place. From Figure 5, fuzzy inference relationship with ANFIS can be established.
Breaking down ANFIS to its FIS part for clearer view, Figure 5 shows relationship between FIS output and inputs.

Three inputs, as mentioned before, are duct opening, robot position and distance. For each input, membership functions are designed so as to represent the behavior of that input as accurately as possible, with respect to expert knowledge.

Input variable ‘duct opening’ (Figure 6) is represented by three membership functions: circular, rectangular and others. Here, the objective is to classify the shape of the opening (circle, rectangle or others) through calculation of circularity made to the image.
The modified generalized bell membership function in Figure 6 can be represented by (2):

$$f(x; a, b, c) = \frac{1}{1 + \left| \frac{x - c}{a} \right|^{2b}}$$  \hspace{1cm} (2)

where variable a,b and c are the parameters. This is chosen due to the nature of classification for this input; ‘circularity’ which fall into the range of certain shape, are most certainly that particular shape (membership function= 1) except when it falls to near to the boundaries.

Input variable ‘robot position’ (Figure 7) and input variable ‘distance’ (Figure 8) behave almost the same and characterized by the same type of membership functions; triangular and trapezoidal.

![Figure 7: Input variable ‘robot position’](image1)

![Figure 8: Input variable ‘distance’](image2)

Intended for both variables, triangular membership function is represented by (3);

$$f(x; a, b, c) = \begin{cases} 
0, & x \leq a \\
\frac{x - a}{b - a}, & a \leq x \leq b \\
\frac{c - x}{c - b}, & b \leq x \leq c \\
0, & c \leq x
\end{cases}$$  \hspace{1cm} (3)

where parameters a and c locate the "feet" of the triangle and parameter b locates its peak is used. This membership function type represents linear increment and decrement within their ranges. For upper most and lower most limit for both, where for input ‘robot position’, these are represented by “too
left” and “too right” membership functions while for input variable ‘distance’, “near” and “far” membership functions are of interest, trapezoidal shaped membership function is used. The function is denoted by equation in (4);

\[
f(x; a, b, c, d) = \begin{cases} 
0, & x \leq a \\
\frac{x - a}{b - a}, & a \leq x \leq b \\
1, & b \leq x \leq c \\
\frac{d - x}{d - c}, & c \leq x \leq d \\
0, & d \leq x 
\end{cases}
\]

where parameters \(a\) and \(d\) locate the "feet" of the trapezoid and parameters \(b\) and \(c\) locate the “shoulders”.

Output variable ‘steering angle’ (Figure 9) is mapped into 45 different membership functions. These reflect marginal values of -45 degree to 45 degree of steering angle. Positive angles are reserved for “steering to the right” while negative means “steering to the left”. Both positive and negative indications are taken with respect to neutral position (0 degree), where tires are aligned with robotic chassis.

![Figure 9: Output variable ‘steering angle’](image)

Below are sample experimental data gained from previous image analysis and experiments. The output values of steering angle are approximately measured for each set of inputs and recorded in Table 3.

| Duct opening | Robot Position | Distance | Steering angle |
|--------------|----------------|----------|----------------|
| 1            | 0              | 30       | -45            |
| 1.55         | 1              | 50       | 5              |
| 1.8          | 1.5            | 60       | 30             |
| 1.95         | 1.8            | 66       | 45             |
| 1.85         | 1.6            | 62       | 35             |
| 1.7          | 1.3            | 56       | 20             |
| 1.97         | 2              | 80       | 45             |

These data are then fed to ANFIS to train the system to recognize and control the maneuver for any HVAC system where the ducting parameters are almost similar to the discussed HVAC ducting type.
3. Result and discussion
Training process is shown in Figure 10 while the result is in Figure 11. Model over fitting is illustrated in Figure 12.

Figure 10: Before training

Figure 11: After training

Figure 11: Input-output surface view
For training purposes, only 21 data sets are used. This is due to the complexity of gaining good samples under current light condition. Also, in order to represent the system as accurately as possible, samples are chosen selectively, where only the best representative for three types of ducting branches are taken; T-branch, elbow branch and left and right branch. Best error is gained after epochs 46.

Enhancement could be done by controlling the luminescent of the light source. Since, inner side of HVAC ducting is reflective, a lot of noises occurred which hindered the acquisition of a good sample. It is difficult to determine blob, border, edges and later the shapes of the duct opening. Good solutions can be achieved by designing a separate subsystem of light control or adding another FIS or ANFIS subsystem focusing on duct opening’s recognition only.

Small training data set (21 data) leaves the system to be fairly weak in generalization. Hence, more data sets are required to make the system more robust to various ducting parameter’s changes.

4. Conclusion
In this paper, ANFIS controller for HVAC service robot is proposed and implemented. 45 rules are implemented with 46 epochs required to train the system. Ultrasonic distance sensor is used together with CCD camera to simplify data acquisition; camera for image processing and ultrasonic sensor for distance. The fusion of 2 sensors eliminate data overload on the system in comparison to stereo vision or perception of depth analysis (monocular vision) for distance measurement. Furthermore, our HVAC service robot platform is the first batch of its class. Efforts are being pushed, mostly towards materializing the concepts and reducing complexities. For future work, ANFIS subsystem will be implemented on robotic arm movement, cleaning brush control and image recognition system.

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