Behavior-Based Neuro-Fuzzy Controller for Mobile Robot Navigation

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The sensors of the mobile robot
The hierarchy of the sensor-based robot behaviors
Select high-level behavior

Select appropriate primitive behaviors

Primitive behavior processing

Goto-XY FIS

Very-Close FIS

Go-Tangent FIS

Follow-Wall FIS

Turn-Corner FIS

Turn-Around

Sensory input

Dead-reckoning input

Command fusion module

Defuzzify module

Crisp turn angle command

Recommended fuzzy turn angle

Not Recommended fuzzy turn angle

Recommended fuzzy turn angle

Recommended fuzzy turn angle

Recommended fuzzy turn angle

Recommended turn angle

FIS = Fuzzy Inference System

The architecture of the behavior-based controller
NEURO-FUZZY IMPLEMENTATION OF 
GO-TANGENT BEHAVIOR

Sensors used in *Go-Tangent-Oblique-Sensor* case.

Sensors used in *Go-Tangent-Front-Sensor* case.
The fuzzy rule for a 2-input and 1-output first-order Sugeno FLC:

\[ IF \, x \, \text{is} \, A_i \, \text{AND} \, y \, \text{is} \, B_j \, THEN \, F_k = p_k x + q_k y + r_k \]

for \( i = 1, \ldots, L; \quad j = 1, \ldots, M; \quad k = 1, \ldots, N; \quad N = L \times M \)

where \( x \) and \( y \) are the linguistic variables, \( F_k \) is the output for the \( k \)-th rule, \( L \) is the size of the fuzzy set \( A \), \( M \) is the size of the fuzzy set \( B \), and \( N \) is the size of the rule base.

For Go-Tangent-Oblique-Sensor ANFIS, \( x \) is the distance to the obstacle with the fuzzy set \( A = \{ \text{short, medium, long} \} \), \( y \) is the speed towards the obstacle with the fuzzy set \( B = \{ \text{slow, medium, fast} \} \). Output \( F_k \) is the turn angle for the \( k \)-th rule, and \( N = 9 \).

For Go-Tangent-Front-Sensor ANFIS both \( x \) and \( y \) are range values. The fuzzy sets for \( x \) is \( A = \{ \text{short, medium, long} \} \), and for \( y \) is \( B = \{ \text{short, medium, long} \} \). Output \( F_k \) is the turn angle for the \( k \)-th rule, and \( N = 9 \).

We have experimented with several types of membership functions for the fuzzy sets \( A \) and \( B \) and with various sizes for \( L \) and \( M \). The triangular membership functions and a size 3 for each of the two fuzzy sets, \( L=M=3 \), were found to be the simplest and best suited for this case.

\[
\mu_{ij}(x_j) = \begin{cases} 
1 - \frac{2|x_j-a_{ij}|}{b_{ij}}, & \text{for } a_{ij} - \frac{b_{ij}}{2} < x_j \leq a_{ij} + \frac{b_{ij}}{2} \\
0, & \text{otherwise}
\end{cases}
\]
Neural Network identification of the Sugeno ANFIS parameters \( \{a_{ij}, b_{ij}\} \) and \( \{p_k, q_k, r_k\} \)
The square elements represent the adaptive nodes depending on the parameter set of the adaptive network. The circles represent fixed nodes, which are independent of the parameter set.

The first layer is composed of adaptive nodes representing the membership functions associated with each linguistic value. The second layer implements the fuzzy rules. It includes only fixed nodes implementing a product $\Pi$ between the membership degrees of the two inputs, $\mu(x)$ and $\mu(y)$, corresponding to the two propositions in the antecedent of each fuzzy rule. The third layer consists of adaptive nodes, which include the output membership function. The other two layers consist of fixed nodes that implement the weighted average for the output $F$ representing the turn angle.

$$F = \sum_{k=1}^{N} (\overline{W}_k \cdot x) \cdot p_k + \sum_{k=1}^{N} (\overline{W}_k \cdot y) \cdot q_k + \sum_{k=1}^{N} \overline{W}_k \cdot r_k$$

As the size of the rule base of the Sugeno FIS is $N=9$, we will have to identify 27 consequent parameters $\{p_1,\ldots,p_9, q_1,\ldots,q_9, r_1,\ldots,r_9\}$. This will be done by a backpropagation NN using a training set $\{x,y,F\}$ of size $P$.

In the forward pass, the input membership functions are fixed and the consequent parameters associated with the output are calculated by applying the least square estimation. Using these parameters, the NN estimates the turn angle. The difference between this estimate and the turn angle’s value from the training set is then backpropagated in a second pass when the premise parameters associated with the input membership functions are calculated.
The 29 points (range, speed, turn angle) data set used for training Go-Tangent-Oblique-Sensor ANFIS. A checking data set was obtained by applying a 10% random noise to the training data set.

The root mean squared errors of the output over 25 training epochs.

One result of the training is the generation of the set of premise parameters \( \{(a_{ij}, b_{ij}) \mid i=1,2,3; j=1,2,3\} \) of the membership functions.

The following figure shows the resulting membership functions for the \textit{range} input and respectively the \textit{speed} input.

It may be interesting to note that, although the training started with symmetric membership functions, their shape eventually became asymmetric after training.
The second result of the training is the generation of the set of consequent parameters \( \{(p_k, q_k, r_k) \mid k=1,2,\ldots,9\} \) in the fuzzy rules. With these parameters the Sugeno fuzzy rules are:

If (Range is Short and Speed is Slow) then (TurnAngle = -3.253 x - 8.858 y + 1.561)
If (Range is Short and Speed is Medium) then (TurnAngle = 4.215 x - 8.077 y + 1.133)
If (Range is Short and Speed is Fast) then (TurnAngle = 0.006 x - 6.715 y + 2.008)
If (Range is Medium and Speed is Slow) then (TurnAngle = 2.967 x - 9.659 y + 3.276)
If (Range is Medium and Speed is Medium) then (TurnAngle = 2.241 x - 8.763 y + 0.933)
If (Range is Medium and Speed is Fast) then (TurnAngle = -1.113 x - 7.021 y + 2.762)
If (Range is Long and Speed is Slow) then (TurnAngle = 3.907 x + 4.525 y - 3.954)
If (Range is Long and Speed is Slow) then (TurnAngle = 1.249 x + 3.560 y - 2.943)
If (Range is Long and Speed is Slow) then (TurnAngle = -0.951 x + 4.639 y - 3.477)
The input-output characteristics of Go-Tangent-Oblique-Sensor ANFIS.
The input-output characteristics of Go-Tangent-Front-Sensor ANFIS.
The behavior-based robot controller has been *tested in four simulated maze-like indoor environments*, for over 2,000 endpoints.

We used the *Rossum’s Playhouse simulation environment*, [9]. We developed our own client application for the behavior-based neuro-fuzzy controller. For a given set of endpoints, the simulation environment monitors the time needed for each target search.

The speed of the robot was set at 0.4 m/s. The four test environments varied in size from 10x10 m to 13x13 m. Traveling between two opposite corners of any environment following a path parallel with the walls, has required 60 seconds. None of the target searches required more than 200 seconds.