Fuzzy Hierarchical Control of Truck and Trailer

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ABSTRACT: This paper demonstrates that problem decomposition leads to more effective knowledge acquisition and improved control performance in fuzzy control. The methodology allows to solve complex control problems (truck backer-upper) without loss of functionality that is very difficult with all-in-one approaches and saves design expenses.

KEYWORDS: Fuzzy control, hierarchical control, problem decomposition.

1 Introduction

Normal driving instincts can cheat us when attempting to back up a trailer truck to a loading dock. The task is so difficult that a lot of practice is needed to master the skill. And even then, when a truck driver backs up toward a loading dock, he or she will go forward and backward numerous times in order to position the truck at the dock successfully. If the driver is not allowed to make forward movements, successful backing becomes improbable.

The problem has become an acknowledged benchmark in non-linear control and as an example of a self-learning system in neural networks was proposed by Nguyen and Widrow in 1990 [1]. Careful experiments of their approach showed that the computational effort is very high [2]. Thousands (about 20000) of back-up cycles are needed before the network learns. Moreover the backpropagation algorithm does not converge for some sets of training samples. Numerous other techniques have been used, including genetic programming [3] neuro-genetic controller [4] and simplified neural network solution through problem decomposition [5]. Very interesting contribution is [6], where up to ten trailers can be controlled representing those as Takagi-Sugeno models and applying linear matrix inequalities method.

A simplified version of the control problem (consisting of the cab part only) has been extensively investigated in the field of fuzzy control [2, 7-11]. In [12] we have shown that hierarchical control system significantly improves control performance and reduces the design load compared to all-in-one approaches investigated by other researcher.

In present paper we extend the hierarchical fuzzy control approach to the full truck backer-upper problem.

2 Object Description

The control object consists of cab and trailer parts (Fig. 1). The trailer position is determined by three state variables x = [-20,20], y = [0, 25], and, Φ_t = [-90°, 270°] - the angle between trailer's onward direction and the x-axis. Length and width of the trailer are 4 and 2 meters, respectively. The cab part is characterized by angle Φ_c = [-90°, 270°] between its onward direction and the x-axis and its dimensions are 2×2 m.

The current implementation of truck backer-upper uses the set of equations from [4].

$$\begin{cases} x(t+1) = x(t) - B\cos(\Phi_t(t)) \\ y(t+1) = y(t) - B\sin(\Phi_t(t)) \\ \Phi_t(t+1) = \Phi_t(t) - \arcsin\left(\dfrac{A\sin(\Phi_c(t)-\Phi_t(t))}{l_t}\right), \\ \Phi_c(t+1) = \Phi_c(t) - \arcsin\left(\dfrac{r\sin(\theta)}{l_t + l_c}\right) \end{cases} \quad (1)$$

where

$$\begin{aligned} A &= r\cos(\theta) \\ B &= A\cos(\Phi_c(t)-\Phi_t(t)) \end{aligned}, \quad (2)$$

and r is the distance covered by the wheels of cab part in one time step (0.1s).

The control goal is to synthesize a controller

$$\theta = f(x, y, \Phi_t, \Phi_c), \quad (3)$$

That would provide that truck arrives from the initial position (x_0, y_0, Φ_0) to the loading dock (x_f = 0, y_f = 0) at a right trailer angle (Φ_c = Φ_f = 90°). Truck only moves backward with the fixed speed 2m/s. The following limitations are being set

$$\begin{aligned} & -70^\circ \le \theta \le 70^\circ \\ & \left|\Phi_c - \Phi_t\right| \le 60^\circ \\ & x > 0 \end{aligned} \quad (4)$$

To evaluate the performance of a control system we use a weighted sum of position and angle errors

$$\varepsilon_c = \varepsilon_x + 0.0267\varepsilon_\Phi , \qquad (5)$$

where

$$\begin{cases} \varepsilon_x = \left| x_f - x(T_f) \right| \\ \varepsilon_\Phi = \left| \Phi_f - \Phi_t(T_f) \right| \end{cases}, \qquad (6)$$

where T_f is the duration of the backing.

3 Control System

The traditional fuzzy logic control – knowledge-based control - would presently fail because there is no explicit knowledge on how to drive the truck and thus we cannot synthesize the controller function (2). This knowledge acquisition problem, however, can be solved by decomposing the control task into three separate parts that could logically then be implemented using three-level control system (Fig. 2).

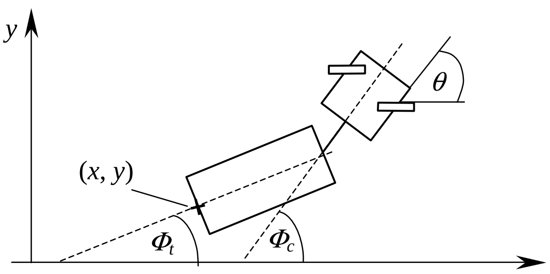

Fig. 1. A driving system consisting of cab and trailer.

The supervisor in Fig. 2 takes position coordinates x, y as its inputs and determines the expected trailer angle for this position. This knowledge is convenient to express linguistically and it has very universal nature. So the supervisor is actually the same as in [12] (due to the different rotating radius of the controlled object slight adjustment of input MFs of the supervisor is necessary that for the sake of convenience is carried out using the scaling factors (k_x = 0.9, k_y = 0.9).

The second fuzzy controller in the control loop creates a mapping $\Phi_t^* - \Phi_t \rightarrow (\Phi_t - \Phi_c)^*$. Because the input of the controller the error of the trailer angle, it can be regarded as a proportional controller that determines the angle difference of cab and trailer parts that is necessary to obtain the expected angle of the trailer. It requires only very primitive understanding of the mechanics of the driving system to reach the conclusion that in order to rotate the trailer part to the left the angle of the cab must be negative and vice versa. Being a SISO system, this functional block can be easily tuned manually and is implemented using fuzzy logic in order to obtain a non-linear mapping that is necessary to achieve high control performance (Fig. 4).

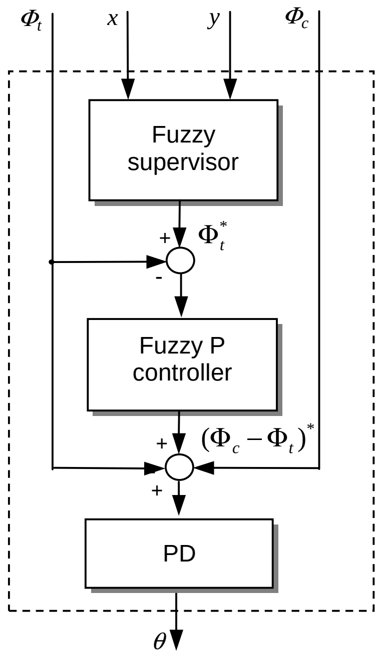

Fig. 2. Fuzzy control block consisting of fuzzy supervisor, fuzzy slave controller and PD controller.

Finally, appropriate steering angle is computed by conventional PD controller (K_p = 12, K_d = 4) that uses the cab and trailer angle difference ($(\Phi_t - \Phi_c)^* - (\Phi_t - \Phi_c)$) as its input.

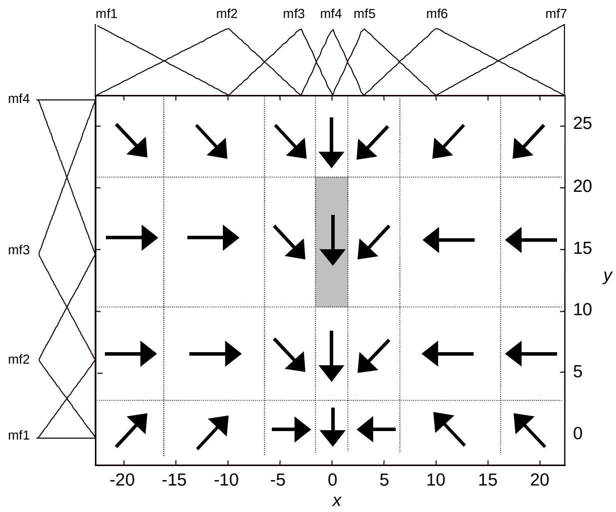

Fig. 3. Rule base of the fuzzy supervisor.

We see that problem decomposition enables us to design the control system because the sub-problems can be accessed individually and in greater detail at the same time. Hierarchical control system is very suitable for the implementation of the multi-level control principle and bringing it back together into one functional block.

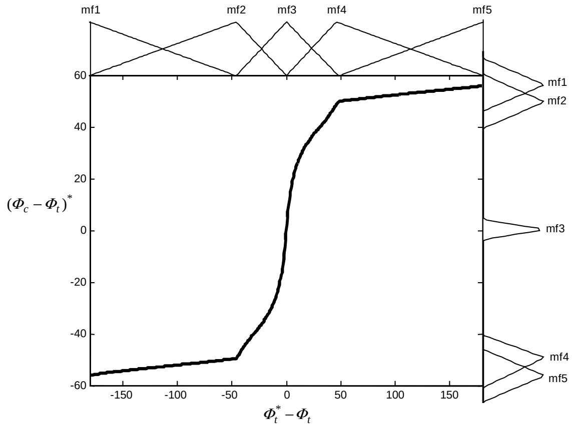

Fig. 4. Fuzzy P controller.

4 Simulation results

In order to test the designed controller, the truck is backed to the loading dock from ten different initial positions (Fig. 5 and Table 1). The selection includes some really difficult starting positions (e.g. 6, 8 and 10). We see that in most cases the error measures (Table 1) are small. Some experiments give rather large error measures, though, that implies that the method has its limitations or perhaps we just require too much. Some interesting backing trajectories are shown in Figs. 6-10.

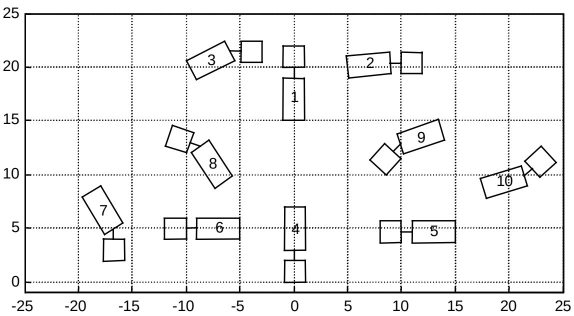

Fig. 5. Initial positions of test drives

Table 1. Initial conditions and control performance.

N_e	x	y	Φ_c	Φ_t	ε_c
1	0.0	15.0	90.3	89.8	0.001
2	5.0	20.0	0.0	5.7	0.004
3	-9.5	19.7	0.0	26.3	0.033
4	0.1	7.0	-90	-90	1.074
5	15.0	4.7	180	180	0.043
6	-5.0	5.0	180	180	1.014
7	-18.8	8.4	-89.2	-59.2	0.002
8	-6.5	9.3	160.5	123.6	1.526
9	13.7	14.2	226.7	199.1	0.001
10	17.6	8.7	42.0	17.2	0.650

5 Conclusions

It has been stated that the more a fuzzy controller resembles the expert's role in a control task, the higher will be the implementation benefit of the fuzzy engine. [13]. As hierarchy is an indispensable part of human reasoning, its reflection in the control structure can be expected to improve the performance of the overall control system.

The main benefit from problem decomposition is that it allows to deal with problems serially rather than in parallel. This is especially important in fuzzy logic where large number of system variables leads to exponential explosion of rules (curse of dimensionality) that makes controller design extremely difficult or even impossible. The "divide and rule" principle implemented through hierarchical control system makes it possible to deal with complex problems without loss of functionality.

It has also been shown that problem decomposition is vital for successful implementation of linguistic analysis and synthesis techniques in fuzzy modeling and control [14] because a hierarchy of fuzzy logic controllers simulates an existing hierarchy in the human decision process and keeps the linguistic analysis less complicated so that it is manageable.

The given application example illustrates well both those statements.

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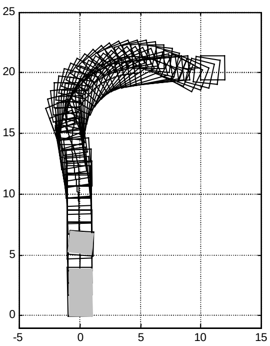

Fig. 6. Backing experiment no. 2.

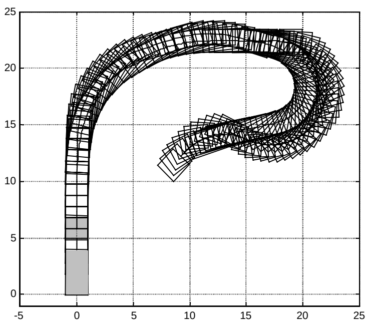

Fig. 7. Backing experiment no. 9.

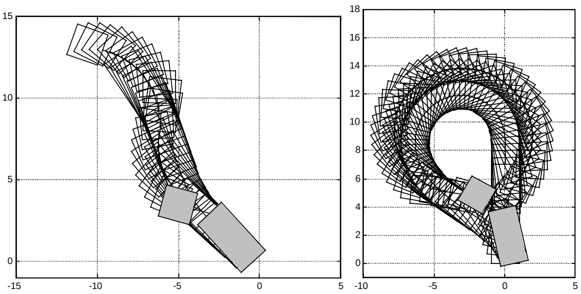

Fig. 8. Backing experiments no. 8 and 4.

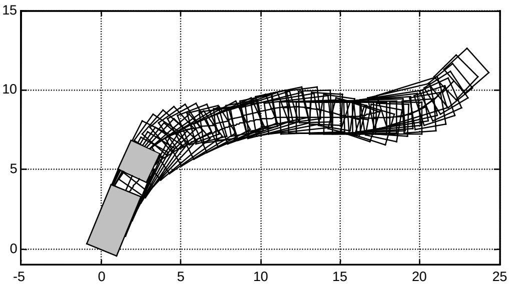

Fig. 9. Backing experiment no. 10.

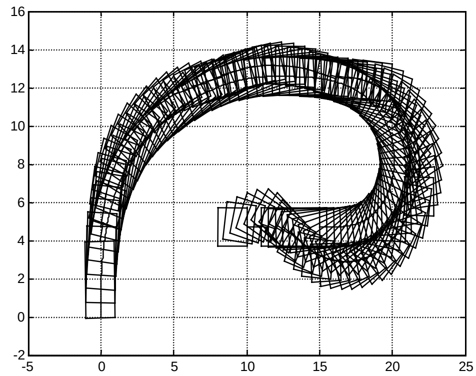

Fig. 10. Backing experiment no. 5.

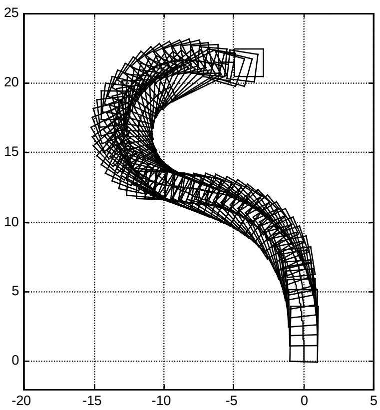

Fig. 11. Backing experiment no. 3.