Fuzzy Backing Control of Truck and Two Trailers

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Abstract **– For a number of years, truck backer-upper problem has served as a benchmark for control among the practitioners of computational intelligence. In our works from the past we have shown how decomposition of the control problem and subsequent segmentation of the control system leads to substantial control performance improvement. In current paper, this control principle is extended to the much more complex two-trailer backing problem with great success.**

I INTRODUCTION

The number of scientific contributions utilizing Nquyen and Widrow truck backer-upper [1] as the test object has grown rapidly and continuously in recent years. Attempts to handle more complex, i.e. multi-trailer systems, on the other hand, are still quite rare. Perhaps the best known of them are the applications of linear matrix inequalities based control for two-, three-, five- and ten-trailer systems [2-4] by Tanaka *et. al.* Kinjo *et. al.* [5, 6] have used genetic algorithms for tuning the neural controllers in the experimental setting very similar to Tanaka's works. These works aim at the stabilization of the system along the x-axis. Few remaining applications [7-9] have either more limited goals or the experimental setting and algorithmic platform is not described in sufficient detail to fully appreciate the contribution of the authors.

From the experiments with the trailer-less truck backer-upper system [10], it has been our understanding that decomposition of the control problem and effective use of fuzzy logic provides an elegant and efficient solution to this challenging task. Current paper that appears as a logical development in the trails of [10-12], presents the fuzzy logic enhanced control system that is able to take full control responsibility over the truck and two-trailer system and deliver it from an arbitrary initial position to a freely positioned loading dock with smooth trajectories and minimal control effort, thus providing the solution to the problem that no sane driver would ever attempt in real life.

II PROBLEM DEFINITION

The driving system (or the car as we shortly address it in this paper) consists of the cab part and two attached trailers (Fig. 1) and is described by five state variables – the coordinates x, y of the reference point placed at the end of the second trailer and Φ_0, Φ_2, Φ_4 that are the angles between x-axis and the cab part, first trailer and the second trailer, respectively. The length (l) and the width (w) of the cab part are both 2m and the dimensions of the trailers are 2×4m.

The challenge in this paper is to design a control system to provide appropriate steering angle θ so that the car will ultimately be positioned at $x = x_f$, $y = y_f$, $\Phi_4 = \Phi_f$ (pre-specified "loading dock").

The kinematics of the car are governed by following equations (taken from [2]):

$$\begin{aligned}
&\Phi_0(k+1) = \Phi_0(k) + \frac{v\cdot\Delta t}{l}\tan\theta(k)\\
&\Phi_1(k) = \Phi_0(k) - \Phi_2(k)\\
&\Phi_2(k+1) = \Phi_2(k) + \frac{v\cdot\Delta t}{L}\sin\Phi_1(k)\\
&\Phi_3(k) = \Phi_2(k) - \Phi_4(k)\\
&\Phi_4(k+1) = \Phi_4(k) + \frac{v\cdot\Delta t}{L}\sin\Phi_3(k)\\
&y(k+1) = y(k) + v\cdot\Delta t\cos\Phi_3(k)\sin\left(\frac{\Phi_4(k+1)+\Phi_4(k)}{2}\right)\\
&x(k+1) = x(k) + v\cdot\Delta t\cos\Phi_3(k)\cos\left(\frac{\Phi_4(k+1)+\Phi_4(k)}{2}\right)
\end{aligned},$$

where $-90° \le \Phi_1 \le 90°$ is the difference between the angles of the cab and the first trailer and $-90° \le \Phi_3 \le 90°$ is the similar difference between the angles of the first and second trailer; L (5m) is the added length of a trailer and its joint, v = -1m/s is backward driving speed and Δt = 0.1s is the sampling time. Also note that steering angle θ is restricted to [-70°, 70°].

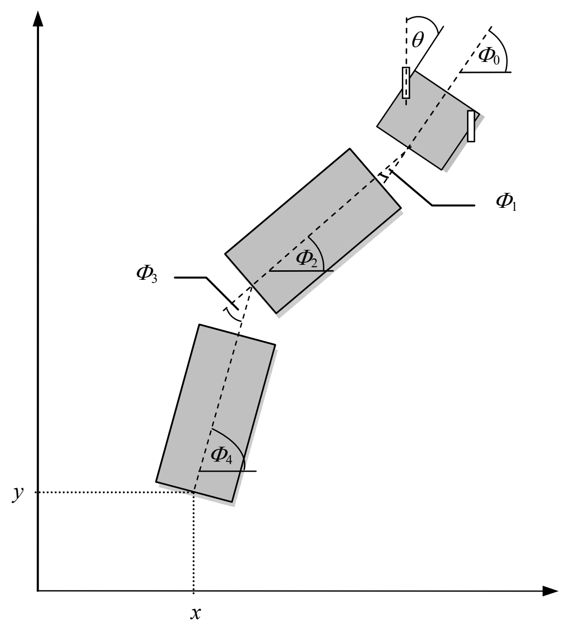

Figure 1. Truck with two trailers and corresponding state variables

III CONTROL SYSTEM COMPONENTS

It was demonstrated in [10] that the control task of driving a simple truck backwards to the loading dock can be solved with less effort if distinction between the tasks of trajectory planning and further determination of the steering wheel angle that would force the car to follow a specified trajectory, is made. Trajectory determination can be carried out quite efficiently in indirect way by defining a desired car orientation angle (that in current application would obviously apply to the second trailer angle Φ_4) for each point in input space (x, y) and it was suggested in [10] that a simple fuzzy logic system called trajectory management unit (TMU) can do the job. TMU actually comes in two parts – the upper one that defines car behaviour for the positive (in respect to y) half plane (Fig. 2) and lower one for the negative half plane (Fig. 3). Note that sole reason for these blocks being implemented as separate pieces is the need to cancel undesirable co-effects from the interpolation of antagonistic rules. For the simple truck navigation the task can then be completed by comparing the desired orientation angle supplied by TMU with the actual orientation of the car and this difference (i.e. orientation error) is supplied to the simple PD controller, which determines appropriate steering angle as a function of the error.

However, as the experimentation with the truck and trailer system in [11] proved, things are not so simple any more if we add a trailer to the truck because of the joint issue. The angle between the cab and trailer parts needs to be manipulated if we expect any control performance and calls for a further segmentation of the control system. Interaction of the cab and trailer parts can be coordinated by a joint controller, which in this case produces an optimal angle between the cab and trailer parts corresponding to the (trailer) orientation error. If orientation error φ is positive, the angle between the trailer and the cab (ξ) must also be positive (and vice versa) and thus the dependence must be monotonously increasing. This single-input single-output functional block is implemented using fuzzy logic in order to obtain a nonlinear mapping that is necessary to achieve expected control performance (Fig. 4). Finally, the difference between expected joint angle and its actual value will be used as an error function for the PD controller defining the steering angle.

Needless to say, in case of truck and two-trailer system things are even more complicated as there are two joints (and respective angles Φ_3 and Φ_1 that need to be manipulated) because of what not one but two joint controllers have to be inserted into the control system. First one governs the relationship between orientation error Φ_{r4} - Φ_4 and expected Φ_{r3}, whereas the second one takes the input from the first and compares it to the actual value of Φ_3 to produce desired Φ_{r1}. Error function for the PD controller will be computed by Φ_{r1} - Φ_1. In summary, this reasoning leads to the principal scheme of the controller depicted in Fig. 5.

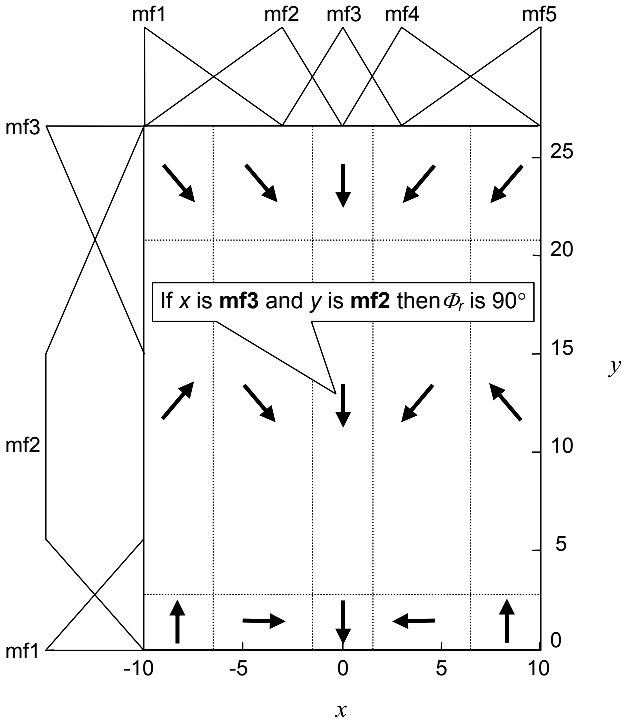

Figure 2. 15 TMU rules responsible for trajectory management when $y > 0$. Each small arrow indicates optimal angle of the car corresponding to the given rule

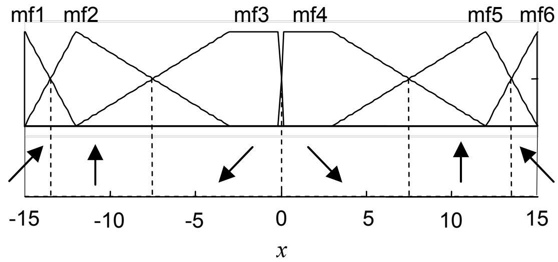

Figure 3. Trajectory mapping unit (lower part)

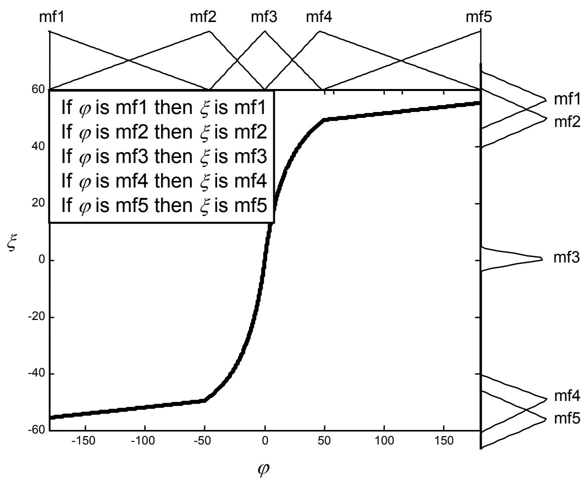

Figure 4. Joint controller.

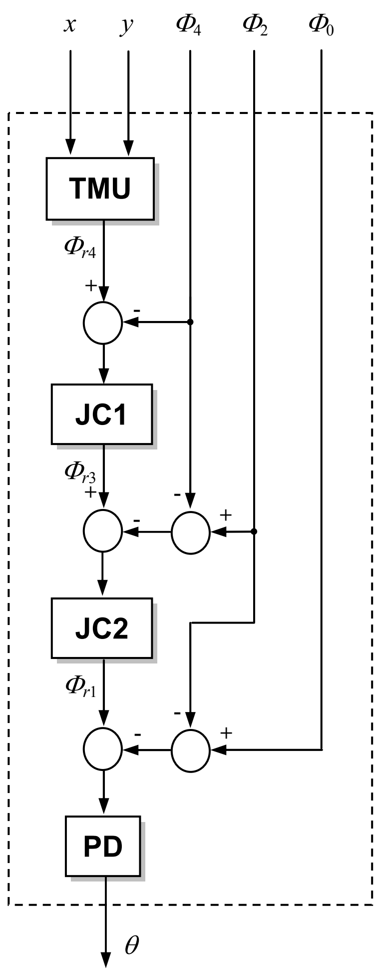

Figure 5. Control system (principal scheme)

IV CONFIGURING THE CONTROL SYSTEM.

In order to achieve good control performance add-ons and further adjustments to the control system depicted in Fig. 5 are required that will be explained in detail in this section. First of all, we need to coordinate the cooperation of upper and lower TMUs with a switching block (Fig. 6) that will see to it that for positives values of y, Φ_{r4} will be supplied by upper TMU and for negative values by its respective counterpart. The effect from using hard limiters at the inputs of fuzzy systems is twofold. First, they are absolutely necessary to guarantee that input values are within the operating range of TMUs. Secondly and very conveniently, these limiters also ensure that car navigation will be governed by appropriate rules even when x and y appear to be outside of the scope of original TMUs. Scaling factors applied to the same inputs, on the other hand, allow us to adjust the TMUs to the substantially increased dimensions of the driving system (compared to the single truck to which the TMUs have been originally optimized for) and with each other. Exactly the same reason calls for the corrective measure of -16 that will be deducted from the value of y fed to the upper TMU – it virtually shifts the rules of the TMU higher so that there is enough space for the u-turn the car is required to make when returning from the negative half-plane.

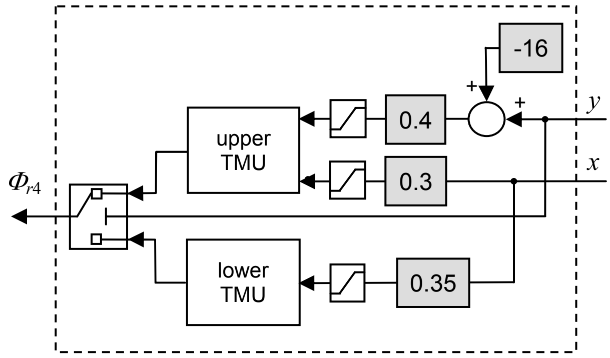

Figure 6. TMU

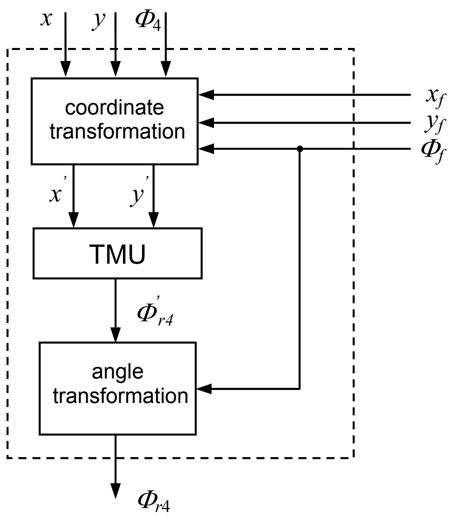

Figure 7. TMU interface

Secondly, fuzzy systems in Figs 2 and 3 are constructed under the assumption that $x_f = 0$, $y_f = 0$, $\Phi_f = 90°$. In order to save ourselves from redesigning these blocks each time the position and/or the orientation of the loading dock is changed, an interface is built between the actual values of x, y, Φ_{r4} and those that will be used for the computations in the subsystem in Fig. 6 (which are denoted by x', y' and Φ'_{r4} in Fig. 7).

The values of x' and y' are obtained using the following formulas:

$$\begin{aligned} x' &= r\cos(90^\circ - \Phi_f + \Phi_4) \\ y' &= r\sin(90^\circ - \Phi_f + \Phi_4) \end{aligned}, \tag{1}$$

where

$$r = \sqrt{(x - x_f)^2 + (y - y_f)^2}\ . \tag{2}$$

Setpoint value corresponding to the given destination (x_f, y_f, Φ_f) is computed by

$$\Phi_{r4} = \Phi'_{r4} + \Phi_f - 90^\circ\ . \tag{3}$$

In result, through all these adjustments, the TMU block in Fig. 5 is updated to the current driving goal and physical characteristics of the controlled object and, in a manner of speaking, generates a virtual force field in the driving area as depicted in Fig. 8.

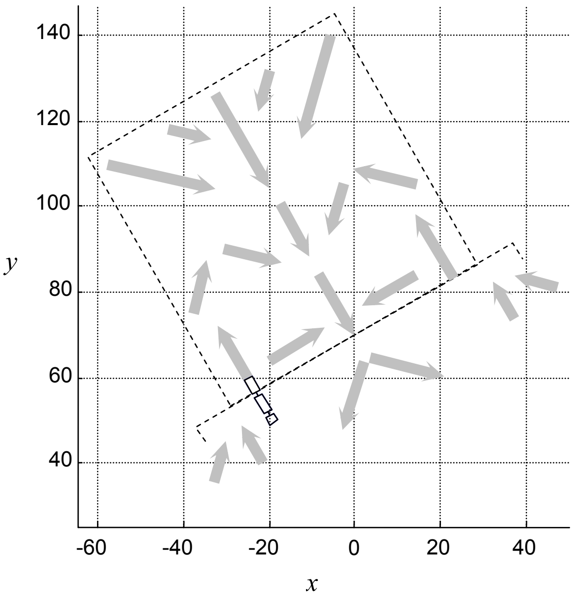

Figure 8. "Force field", generated by TMU

Scaling factors come also very handy for adjusting the joint controllers. It can be deducted that for minimizing the difference between Φ_4 and Φ_{r4} we need a negative angle of Φ_3 if Φ_{r4} - Φ_4 is positive (and vice versa), thus the function performed by the joint controller 1 should be monotonously decreasing. This can be accomplished by a negative scaling factor on the respective controller output (Fig. 9). The same applies for the second joint controller - for minimizing the difference between Φ_3 and Φ_{r3} we need a negative angle of Φ_1 if Φ_{r3} - Φ_3 is positive (and vice versa). The absolute values of scaling factors, on the other hand, enable us to impose limitations on Φ_1 and Φ_3 and specify sensitivity of joint controllers. It turns out that the first joint should be less receptive to control actions that propagate from the wheels of the cab and thus requires lower values for both scaling factors. In fact, appropriate selection of the output scaling factor value of first joint controller is critical to the overall control performance – even a small decrease e.g. a value of -0.8 leads to proportionally higher maximum values of Φ_3 that make the system unstable and jeopardize the control goal.

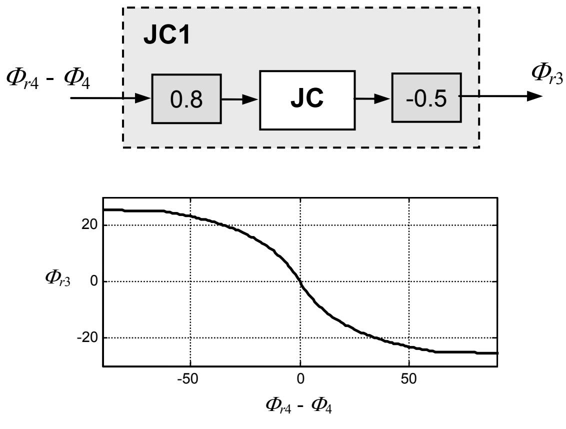

Figure 9. Joint controller No. 1

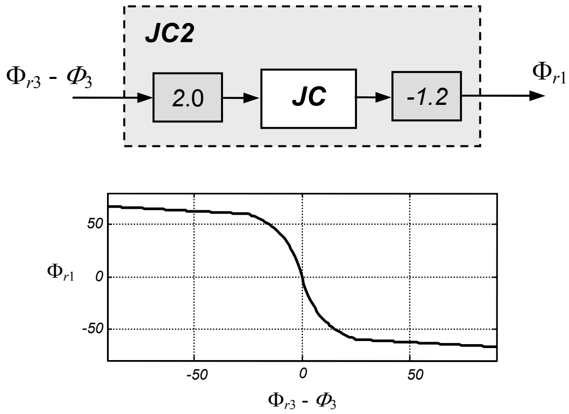

Figure 10. Joint controller No. 2

Finally, the block that translates the difference between Φ_{r1} and Φ_1 into appropriate steering angle θ is in this application yet another scaling block (or a P-controller with K_p = -3). The latter has a negative sign because we need negative steering angle if Φ_{r1} - Φ_1 > 0 (and vice versa). Note that direct linear transformation is valid in the range [-23.3°, 23.3°] of Φ_{r1} - Φ_1 because of the physical restriction on θ.

V RESULTS

This section presents the backing results from 10 randomly selected initial positions (Table I) to the loading dock situated at (x_f = 0, y_f = 70) with Φ_f = 120°. In backing up the truck and trailer systems there is one particularly unfortunate position well known to drivers called jackknife, which means that either Φ_3 or Φ_1 equals -90° or 90°. In jackknife position car starts moving along a circle, never leaving it, never arriving to the loading dock and.thus becoming uncontrollable car. Since the joint controllers keep the values of Φ_1 and Φ_3 well under -90°/90°, it follows that whether the car goes to jackknife or not, depends on the initial values of Φ_1 and Φ_3 only. With the help of selected simulations it was found out experimentally that car goes jackknife if the absolute values of Φ_1 and Φ_3 both exceed 60° (if they have the same sign) or 50° (if they have different signs) and as a precaution, in initial conditions the absolute values of Φ_1 and Φ_3 are therefore kept below 45 degrees. Backing trajectories (for the sake of the clarity of the illustration, only the trajectory of the second trailer is drawn at each 20^{th} sampling step) from these initial positions are depicted in Fig. 11. Backing quality is evaluated in terms of backing errors (a weighted sum of distance and orientation errors at the loading dock), computed by

$$\varepsilon = \varepsilon_d + 0.0267\varepsilon_\Phi , \qquad (4)$$

where

$$\begin{cases} \varepsilon_d = \sqrt{(x_f - x(T_f))^2 + (y_f - y(T_f))^2} \\ \varepsilon_\Phi = \text{abs}(\Phi_f - \Phi_4(T_f)) \end{cases} , \qquad (5)$$

where T_f is the duration of the backing. These backing errors for all 10 test drives are visualized in Fig. 12.

One must note that at current backing speed (1m/s) car advances 10cm within one sampling interval, and this uncertainty alone may be the reason why backing error is as high as 0.1 even if the car arrives at the loading dock at perfect angle. As it turns out, however, actual error values remain the within the range [0.1, 0.7]. When we recall that total length of the driving system is 12m, such inaccuracy is really marginal, besides, the backing trajectories appear to be very smooth. In order to demonstrate that such control quality is accomplished with minimal control energy, control action θ along with the dynamics of Φ_1 and Φ_3 for the one of the curviest backing trajectories (drive No. 4) are depicted in Fig. 13.

TABLE I

TEST DRIVE INITIAL CONDITIONS

No.	$x(0)$	$y(0)$	$\Phi_0(0)$	$\Phi_2(0)$	$\Phi_4(0)$
1	28.3	124.9	115.2	145.7	103.2
2	18.1	21.8	345.6	357.2	340.4
3	29.4	138.8	268.0	277.7	294.2
4	-44.1	114.7	96.5	108.2	71.5
5	10.3	72.7	158.4	146.7	104.9
6	-45.0	79.8	336.0	342.8	352.9
7	-8.5	45.7	246.0	241.7	251.4
8	46.7	61.5	162.2	153.3	184.3
9	37.0	38.7	324.6	335.8	346.7
10	-49.0	43.0	2.0	23.0	43.8

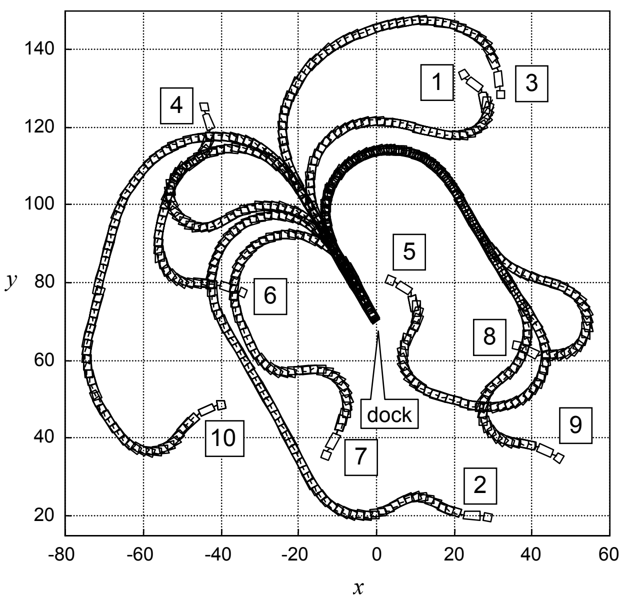

Figure 11. The backing trajectories

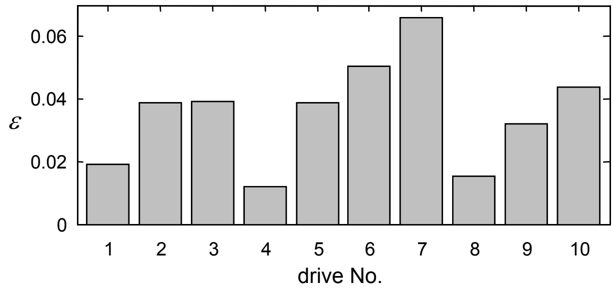

Figure 12. The backing results in terms of final positioning errors

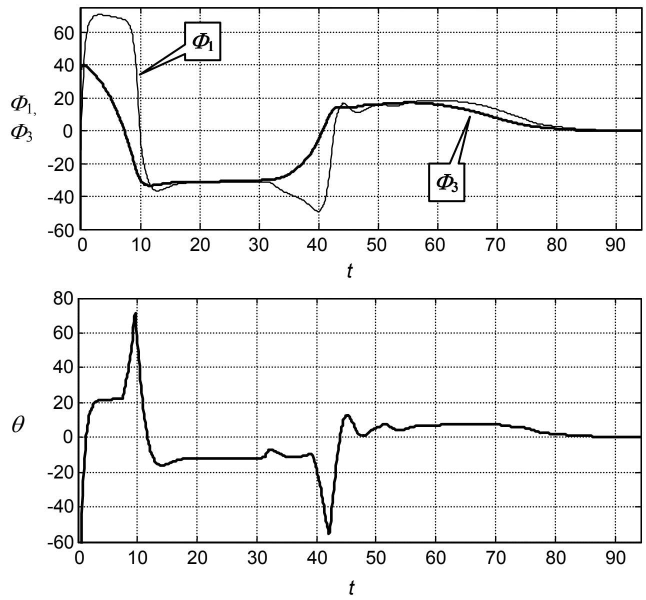

Figure 13. Angles Φ_1 and Φ_3 (above) and steering angle (below) during the backing (drive No. 4)

Though the control system is optimized for and the experiments carried out at the fixed backing speed of 1 m/s, it is capable of controlling the car at considerably higher speeds. It can be observed though that control becomes gradually less stable as speed increases. First such effects become apparent if speed reaches 5m/s and though the car is still able to follow the trajectory to the loading dock, the action at the steering wheel becomes more and more frantic from this point. The system becomes completely uncontrollable if speed exceeds 10m/s. It is, however, highly doubtful if anyone has ever witnessed a two-trailer truck storming backwards toward the loading dock at such speeds in real life.

VI CONCLUSIONS

In this paper we described a control system for the truck and two-trailer system, fully capable of steering the car from a virtually arbitrary initial position to the pre-specified loading dock. Problem decomposition leads to a hierarchical control system that focuses on trajectory management and subsequent trajectory-driven manipulation of trailer angles. These principal tasks are carried out by very simple functional blocks implemented by the means of fuzzy logic, whereas additional components such as coordinate transformation blocks and scaling factors make the system easily reconfigurable and extendable if the need arises. The main benefit from problem decomposition, however, is that it allows us to deal with resulting smaller problems individually that ultimately leads to the transparent control system with good control performance and no loss in functionality. Fuzzy systems similarly benefit from having a small number of input variables that keeps the number of fuzzy rules at a reasonably low level that is especially useful when tuning the subsystems for best performance.

The results strongly suggest that the control approach adopted in this paper could be further developed to facilitate the control of trucks with even more trailers.

VII ACKNOWLEDGEMENT

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