EMS-Vision: Enhanced Abilities for Locomotion

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Abstract

Over the last years, the expectation based multifocal saccadic vision system (EMS-Vision) for autonomous vehicles has been developed. This not only required an adaption and restructuring of vehicle guidance but also a development of enhanced abilities for locomotion. In the course of integration of vehicle guidance to the new system, the locomotion part received a new structure and has been extended. By means of the "Turn-Off" maneuver it is shown how single phases of a driving maneuver are triggered and how the transition conditions are generated. During a maneuver phase, command variables for the longitudinal and the lateral controller are generated. The locomotion unit is implemented on both test vehicles VaMoRs *and* VaMP *of UBM. Only the hardware specific part depends on the type of vehicle, otherwise, vehicle guidance is the same for both experimental vehicles.*

Keywords autonomous vehicles, vehicle guidance, feedforward control

1 Introduction

In 1992 N. Müller presented road vehicle guidance for turning off onto a cross road [1]. Additionally, in [2] model based image processing for perception of an intersection (following the 4-D approach), gaze control of a pan and tilt platform for fixation of the intersection and the off-going road as well as navigation for turning off are described in detail.

The system of vehicle guidance, image processing and gaze control had been implemented on special computer hardware (transputer net). Over the last years, UBM's experimental vehicles VaMoRs and VaMP have been equipped with commercial off-the-shelf (COTS) components. In parallel a perceptual system for autonomous vehicles called EMS-Vision (Expectation based Multifocal Saccadic Vision) has been developed and realized, see [3].

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The maneuver for turning-off onto a crossroad will be used as an example to explain the integration of vehicle guidance with the EMS-Vision system and the implementation on the new COTS-Hardware.

2 Mathematical Foundations for Turning-Off

Figure 1 shows a typical intersection (non-orthogonal T-junction) with another road. The task is to turn-off onto the road going to the left. The own road runs approximately straight into the area of turn off. The angle of the turn-off ψ_{CR_CS}, the lane widths b_{CR} und b_R, the radius r_{CS} and the position of the turn-off relative to the vehicle are perceived by real time image processing (see [4]).

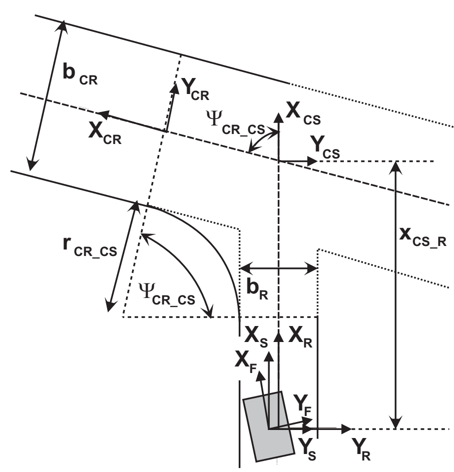

Figure 1: Intersection geometry

Based on the approach shown in [1] and [2], the activities of vehicle guidance for executing the "Turn-Off" maneuver can be explained as follows:

A border line is defined consisting of line pieces that are parallel to the lane borders and a circular arc segment. The center of the rear axle of the road vehicle shall closely follow it. For then it is guaranteed that the inner bend rear wheel will not cross the kerbstone, as long as the distance of the border line to the road border is larger than half the width of the vehicle. Because road vehicles can not follow a discontinuity in curvature as occurs at the transition from straight line to circular arc without stopping. The trajectory of the center of the rear axle has to be approximated by clothoids. Starting curvature of the path is zero as the vehicle is going straight on, the maximum curvature in the vertex of the curve is the inverse radius of the circular arc. Turning into and exiting out of the curve may be chosen as symmetric to the vertex point, therefore, only the initial part will be treated subsequently. As the clothoid path must not cross the border line to the left at any point, a little deviation to the right has to be headed for. So the clothoid path looks as shown in fig. 2.

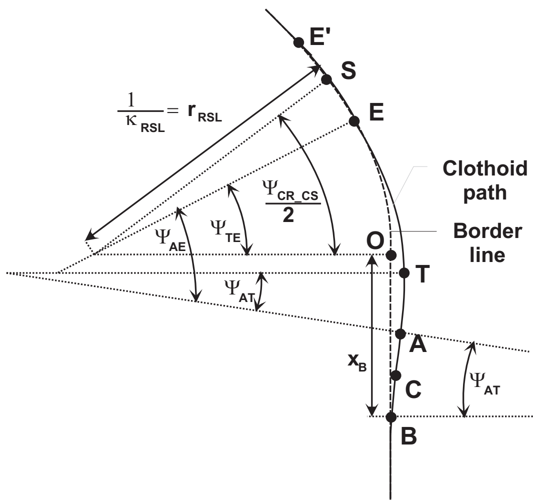

Figure 2: Vehicle path for turning into a curve

At the depicted points the following conditions can be set up:

B	$\psi_B = 0$	$\kappa_B = 0$	$\lambda_B = 0$
C	$\psi_C = \psi_{AT}/2$		
A	$\psi_A = \psi_{AT}$	$\kappa_A = 0$	
T	$\psi_T = 0$		
E	$\psi_E = \psi_{AE} - \psi_{AT}$	$\kappa_E = \kappa_{RSL} = \frac{1}{r_{RSL}}$	
S	$\psi_S = \psi_{CR\_CS}/2$	$\kappa_E = \kappa_{RSL} = \frac{1}{r_{RSL}}$	

Here ψ means the angle of the path tangent to the border line, κ is the curvature of the path and λ is the steering angle of the front wheels of the vehicle.

In order to determine the position of these points, the steering rate c_λ is given as piecewise constant at some value to be properly defined for both left and right turns. This results in a steering angle time history as shown in fig. 3.

So, the magnitude of the steering rate is the only free parameter of the feedforward control maneuver.

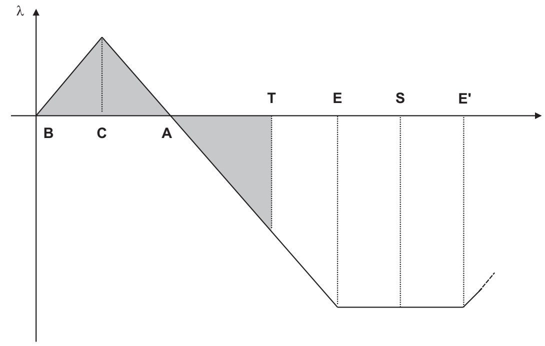

Figure 3: Steering angle in dependence of covered distance

The geometry of a linear planar single track model for road vehicles [5] with a wheelbase l_L leads to

$$\lambda = \lambda_0 + c_\lambda \cdot t = \lambda_0 + \frac{c_\lambda}{v} \cdot l \qquad (1)$$

with l ...covered distance

and v ...speed.

$$\kappa = \frac{1}{l_L} \cdot \sin(\lambda(l)) \qquad (2)$$

Clothoids are described by

$$\psi = \int \kappa \, dl \qquad (3)$$

$$x = \int \cos(\psi(l)) \, dl \qquad (4)$$

$$y = \int \sin(\psi(l)) \, dl \qquad (5)$$

with x, y being Cartesian coordinates. Two quantities can be found easily:

$$l_{AE} = \frac{v \cdot l_L \cdot x_{RSL}}{c_\lambda} \qquad (6)$$

as length of the path between A and E.

$$\psi_{AE} = \frac{1}{2} \cdot \kappa_{RSL} \cdot l_{AE} \qquad (7)$$

is the included angle.

In order to determine the distance x_B from point B to point O the pathlength l_{BA} is needed. It can be read from fig. 3. If approximately $\sin(\lambda) = \lambda$ the enclosed surface between B and A and A and T has to be of same size as $\psi_B = \psi_T = 0$. So

$$l_{BA} = \sqrt{2} \cdot l_{AT}. \qquad (8)$$

l_{AT} then can be evaluated by

$$y_{BC} + y_{CT} + y_{TE} - r_{RSL} \cdot (1 - \cos(\psi_{TE})) = 0 \qquad (9)$$

An approximation of $\cos(\psi_{TE}) = 1 - \frac{\psi_{TE}^2}{2}$ leads to a fourth degree equation for the ratio $s = \frac{l_{AT}}{l_{AE}}$:

$$3s^4 + 3\sqrt{2}s^3 + 6s^2 - 1 = 0 \quad (10)$$

One solution to this equation is $s_0 = 0.33$. With $x_B = x_{BC} + x_{CT} + x_{TE} - r_{RSL} \cdot \sin(\psi_{TE})$ the searched distance is:

$$x_B = l_{AE} \cdot (\frac{1}{2} + \sqrt{2}s + \frac{s^2}{2}) \quad (11)$$

The ratio s strongly depends on an initial lateral deviation y_B of the vehicle to the border line. The dependence is square root like and is approximated by

$$s = s_0 \cdot (s_1\sqrt{Y} + s_2 \cdot Y) \quad (12)$$

with $s_1 = 5.3$, $s_2 = -2.0$
and $Y = \frac{y_B \cdot r_{RSL}}{l_{AE}^2} + \frac{1}{24}$.

This equation has real solutions, as long as the condition

$$y_B \geq -\frac{1}{24} \cdot \frac{l_{AE}^2}{r_{RSL}}$$

is kept.
More negative values of y_B indicate that the deviation to the left is big enough that the vehicle can turn to the right. The steering rate then has to be reduced to

$$c_\lambda = \frac{v \cdot l_L}{r_{RSL} \cdot \sqrt{24 \cdot r_{RSL} \cdot (-y_B)}} \quad (13)$$

as a result of $s = 0$ in eq. 12.

By allowing any initial lateral deviation, a limiting case for conventional road vehicles can be treated: the turning circle.

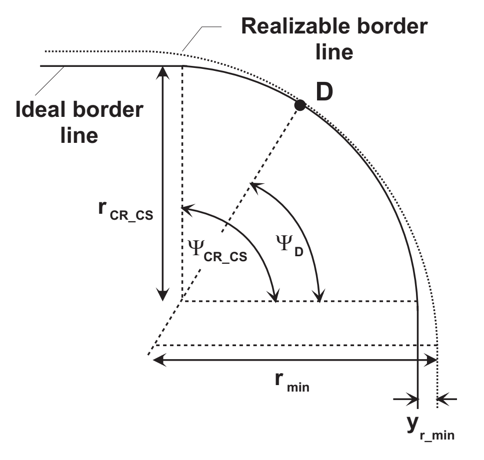

Figure 4: Turning off with minimal radius

If a border line has to be dealt with, the radius of which is less than the turning radius of the vehicle, another border line with a radius of the same size as the turning radius of the vehicle is superimposed on the original one (see fig. 4), e.g. if $r_{CR\_CS} < r_{min}$ than $r_{RSL} = r_{min}$ else $r_{RSL} = r_{CR\_CS}$. The two lines will touch each other in exactly one point D of their circular arcs to be freely chosen. So, in point B an additional positive lateral deviation y_{r_min} seems to arise.

Depending on the choice of D the vehicle will have to draw back to the right before turning left.

Note that this approach takes into account neither slippage of the wheels on the ground nor any lateral sliding. In order to avoid these effects, speed has to be reduced by the longitudinal controller.

The steering rate c_λ is the feedforward variable for the lateral controller. c_λ is computed during the approach to the intersection. A positive steering rate means a "Turn-Off" maneuver to the right, a negative rate means one to the left.

3 Structure of the "Turn-Off" Maneuver

The absolute value of the feedforward variable c_λ is piecewise constant (see fig. 3) but the sign is different.

If a swinging back is necessary, the negative value of the precomputed steering rate between the points B and C is set. Between the points C and E the center of the rear axle moves on a clothoid because the precomputed constant c_λ is set. Between E and E' the vehicle drives on a circular arc with $c_\lambda = 0$. After point E' the negative value of the precomputed steering rate is set again. In this phase a state feedback controller of third order with the state vector $[\lambda, \psi_{R\_F}, \Delta y_{R\_F}]^T$ is applied, additionally. ψ_{R_F} and Δy_{R_F} are now referred to the new own road, the previous cross road. Thereby it is achieved that the lateral offset to the centerline of the new road is a minimum.

The sequence of single "Turn-Off" phases for lateral control is implemented using an automaton. The transition conditions for the automaton result from reachin the points B, C, E and E' (for automata statecharts see [6]). Fig. 5 shows the statechart for the "Turn- Off" maneuver.

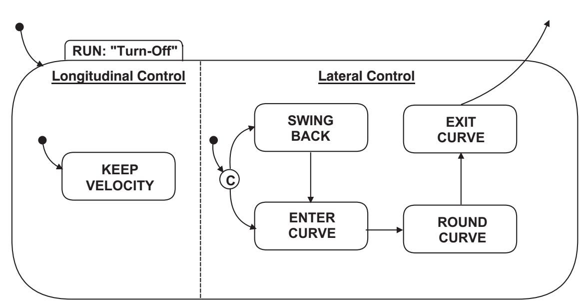

Figure 5: "Turn-off" statechart

There are two parallel automata, one for longitudinal control, the other for lateral. If it is necessary to swing back initially, the lateral automaton starts at the automaton state "SWING

BACK" otherwise it starts at "ENTER CURVE". All automata states of the lateral automaton are passed through successively. In parallel, the longitudinal automaton is running. The longitudinal automaton for the "Turn-Off" maneuver has only one state "KEEP VELOCITY".

In fig. 5 the computational part of the maneuver, calculation of the required steering rate c_λ, velocity v and of the transition conditions to switch from one automaton state to another, is not represented.

For a consistent representation of abilities like the "Turn-Off" maneuver, in the EMS-Vision system the following characterization of abilities has been developed using statecharts (see fig. 6).

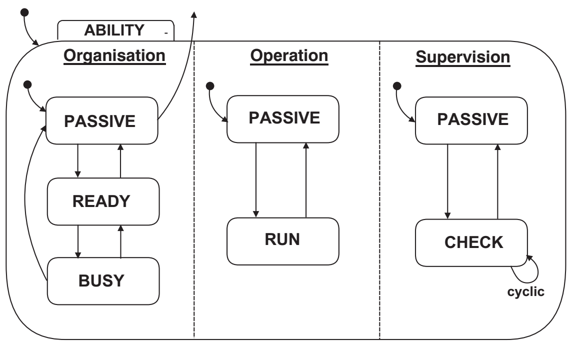

Figure 6: Representation of abilities with statecharts

4 Integration of the "Turn-Off" Maneuver into Control Flow

An ability consists of three parallel statecharts. The first is for Organisation, the second one for Operation and the third for Supervision of the ability. If an ability is initialised, all three statecharts start with their "PASSIVE" state. The Supervision part switchs directly from "PASSIVE" into its "CHECK" mode. In this state all required components (controllers, e.g. longitudinal or lateral controller; hardware, e.g. steering, gas or brake; subsystems, e.g. vehicle subsystem) are checked cyclicly, if they are ready for use. If all checks are successful, the Organisation statechart switches from "PASSIVE" to "READY". If one of the following cyclic checks is not successful, all three parallel statecharts are reset to their initial state "PASSIVE". Else the Organisation statechart waits for a message from a higher level decision unit (see fig. 7). This message indicates, that all other needed abilities, e.g. image processing abilities, are existing and causes the Organisation statechart to switch from "READY" to "BUSY". In this state all calculations like the ones of section 2 are performed. Conditions for the transition from "PASSIVE" to "RUN" state of the Operation statechart are calculated also in the state "BUSY" of the Organisation. If conditions for transition are accomplished, the special "RUN" automaton like the one of fig. 5 is started. The output of control of each "RUN" automaton state is done on the complementary systems dynamics level. At the time when the "RUN" automaton" is finished all statecharts switch to "PASSIVE". The "ABILITY" statechart is left by the transition from "PASSIVE" of the Organisation statechart to the outside if an order arrives from a higher level.

In order to turn-off at an intersection like the one of fig. 1 at least one other ability than "Turn-Off" has to be available. The second ability needed is "Follow Lane".

For choosing the proper ability for the respective situation, in [7] a hierarchical system architecture has been suggested. This architecture includes a Behavior Decision for Locomotion (BDL) unit, as can be seen in fig. 7, for keeping local decisions for locomotion consistent. The task of Central Decision (CD) is to coordinate all abilities needed for a maneuver and to resolve conflicts between abilities.

If a vehicle approaches to an intersection in the "Follow Lane" mode, CD initializes the abilities for turning off. The sequence of wanted abilities are pretended in the mission plan (see [8]). At first view, this is the ability of vehicle guidance explained in section 3. But abilities to perception an intersection (see [4]) or to control the gaze direction (see [9]) are also necessary. If all components needed announce their readiness, CD causes the abilities to switch to their "BUSY" mode. This means for locomotion that now BDL is the decision-maker. BDL handles informations for the actual and the next ability like those of section 3. Additionally, relevant variables and their variances, e.g. distance to intersection are considered. If, for instance, the variance of distance to intersection is too large, no "Turn-Off" maneuver will be triggered by BDL. If all informations are positive, BDL will cause the desired ability to switch to its "RUN" mode and will stop the actual ability. For monitoring and conflict handling BDL announces its status, orders and decisions to the higher level CD.

5 Implementation on the EMS-Vision Hardware

As can be seen in [3] COTS computer hardware is used generally for the development of the EMS-Vision system. Only the "Platform subsystem" and the "Vehicle subsystem" are special computer hardware. The "Vehicle subsystem" is a transputer network with four transputer nodes (T805). The transputer network is connected to the "Behavior PC" via a transputer link. Sensor signals like those from inertial or odometry sensors are read in by the "Vehicle subsystem". Also, all actuators (gas,

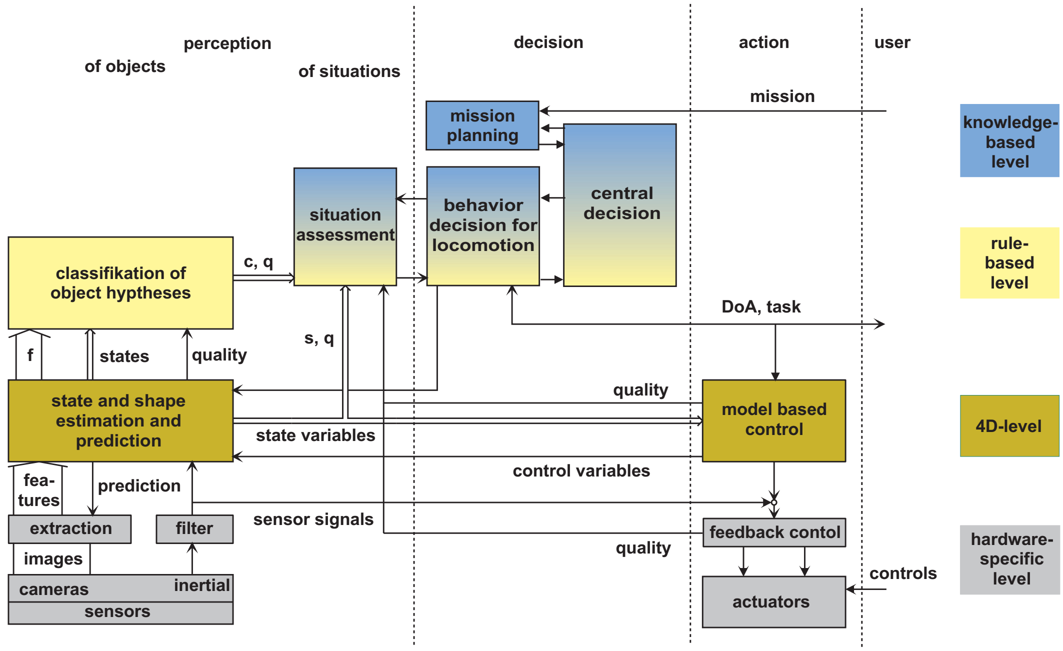

Figure 7: Hierarchical system architecture for autonomous vehicles; f: features, s: state variables, q: quality, c: classes, DoA: Degree of Automation (see also [7])

brake, steering) are controlled by the "Vehicle subsystem". In addition, all time critical controllers (velocity-, deceleration-, steering-controller and so on) are implemented on the "Vehicle subsystem", as the transputer net guarantees real-time feedback control loops. The cycle times of feedback controllers range from 7ms up to 40ms. In this manner, the locomotion system is distributed on a PC and the transputer net. The transputer link between the PC and the transputer network have to be controlled by the locomotion software. The part of the locomotion software, which is placed on transputer nodes, is implemented in C. Only this part is devided into two specific parts, one for each test vehicle. The rest of the locomotion software, which is running on PC, is implemented in C++. All software components on PC are the same for both vehicles. Additionally, the locomotion software on PC is an EMS-Vision process (see [3]) and so data from vehicle control can be exchanged with other EMS-Vision processes via `DOB`.

6 Experimental Results

Figure 8 shows preliminary results of real "Turn-Off" maneuver. The steering angle and rate are represented.

Until cycle 3900 the test vehicle performs a "Follow Lane" maneuver, then the "Turn-Off" maneuver is performed. In this case no "SWING BACK" mode is necessary. During the "Turn-Off" maneuver, the steering is controlled by a piecewise constant steering rate (absolute value: 6.3 deg/sec). This results in the progression of the steering angle of fig. 8. Comparing with fig. 3, in the progression of the steering angle of figure 8 is there no phase with constant steering angle, because no "ROUND CURVE" mode with $c_\lambda = 0$ is necessary for performing this "Turn-Off" maneuver.

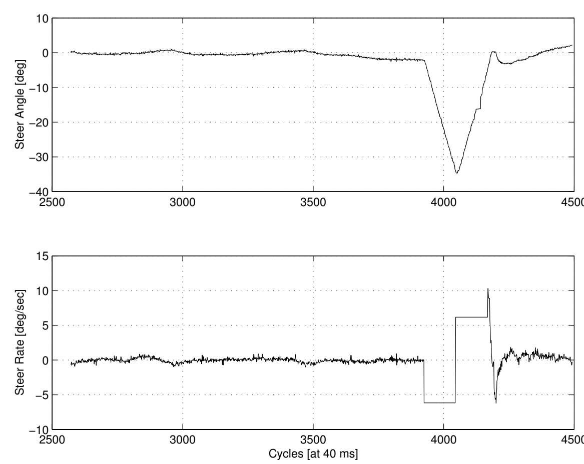

Figure 8: Steering angle and rate

7 Conclusions and Outlook

The "Turn-Off" maneuver served as an example for demonstrating how single abilities of vehicle locomotion can be combined with other ones. Besides, a consistent schematic diagram for representing abilities has been developed. The abilities are administered and triggered by several decision instances. The cooperation of these different decision instances has been explained using a hierarchical system architecture for autonomous vehicles, implemented on the experimental vehicles VaMoRs and VaMP. The architecture is the same for both vehicle, only the hardware specific part is different. Focus of current work is to generalize other abilities of vehicle locomotion by using this approach, in order to perform more complex missions [3], [8].

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