Low-level controllers realizing high-level decisions in an autonomous vehicle

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Low-level Controllers Realizing High-level Decisions in an Autonomous Vehicle

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***Abstract*— The *Urban Challenge 2007* is a research program conducted in a competitive format to address the challenging aspects of letting vehicles accomplish missions in urban scenarios fully autonomously. AnnieWAY is one out of eleven autonomous vehicles that entered the finals. As it turned out, one of the major difficulties is the combination of different algorithms for different tasks to a functioning unit. This contribution describes AnnieWAY's interface between high-level decision making (path planning) and low-level control and provides herewith a simple but robust solution to handling the vehicle's physics.**
Additionally, the longitudinal and lateral controller, which convert the interface's values ultimately to the manipulated variables are described in detail.

***Index Terms*— Orbital tracking, autonomous vehicle, interface, longitudinal control, lateral control**

I. INTRODUCTION AND PROBLEM FORMULATION

Since the distances to dynamic objects are fairly big in the *Urban Challenge* 2007 competition, for high-level decision making the problem of trajectory planning (coordinates of the desired vehicle position as a function of time) can be reduced to a combination of path planning (path geometries with no time dependencies) and determining the free section of the path rather than an exact desired position. The longitudinal strategy is thereby assigned to a lower level, which evaluates the free section of the path and induces the vehicle to go faster or slower. The information transfer of the interface is undertaken by so-called curve points, a discrete representation of the path geometry as described in Section II.

As the emphasis of the competition is on low to medium velocities, the non-holonomic single track model holds and an orbital tracking controller (e. g. [3]) is chosen for the lateral dynamics in Section III. This offers the advantage of a velocity independent transient lateral behavior for the closed loop system. Suppose the vehicle had an offset from the planned path of a couple centimeters caused by sensor drift of the navigation system, the lateral controller would reduce the error over a certain traveled distance rather than over time and avoids unpredictable overshoots of the front end which might lead to collisions.

From the longitudinal controller's point of view, the vehicle drives on rails, as the lateral controller minimizes the lateral offset. Thus, the longitudinal control strategy faces solely the task of following moving objects, stopping at certain points, maintaining the maximum speed, and changing direction along the given path. For this purpose different controllers are designed in Section IV that are included in an override control strategy ensuring bumpless transfers between them. The output of every longitudinal controller is the vehicle's acceleration a. This acceleration will be converted to the manipulated variables accelerator pedal value ϕ_{gas} and brake pressure p_{brake} in a cascaded acceleration controller exceeding the scope of this paper.

II. UNIVERSAL INTERFACE

As shown on the left of Fig. 1, there are two different sources generating the desired path for the vehicle. Roughly speaking, the road network definition file (RNDF, see [1]) can be considered a railroad system which keeps the vehicle movements to the road center. An additional filter accounts for small obstacles on the lane boundary and provides smooth transients between road segments to ensure the drivability of the path. By contrast, only based on sensor information, a discrete search algorithm paves its way through so called zones [1] or executes parking maneuvers as shown in Fig. 2. Both sources output points along the desired path that are combined with additional specifications from the longitudinal strategy, such as the position of the next stop on the path.

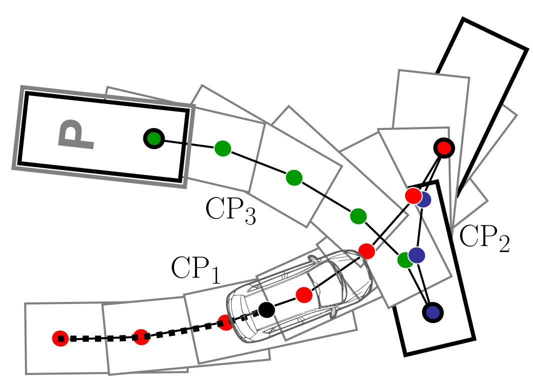

Fig. 2. Three consecutive sets of curve points

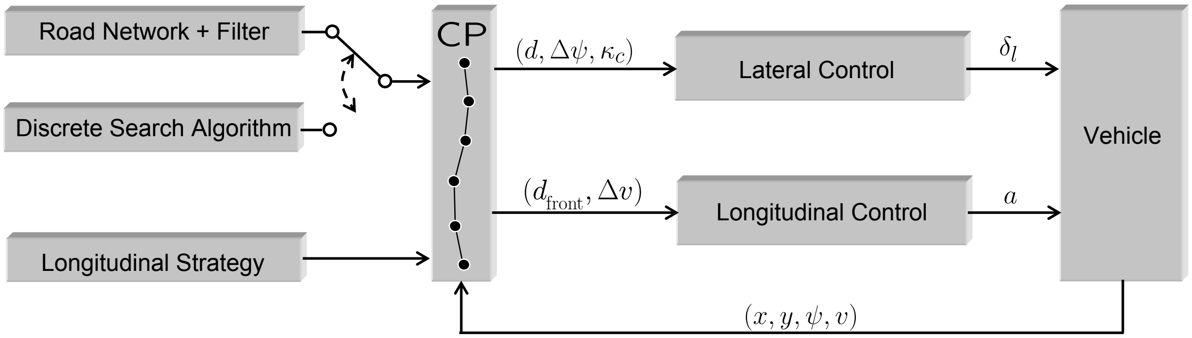

Fig. 1. Interface to lateral and longitudinal control

A. Curve points

All traffic scenarios that come across in the competition can be reduced to three $cases$. The vehicle travels along the desired path and

1) has to stop at a certain distance ahead ($cs\_stopdistance$),
2) has to follow another moving object driving at a certain distance and velocity ahead ($cs\_following$),
3) or the section in direction of motion is clear (cs_drive).

The information about the desired behavior is transferred by the interface with

- n curve points $\xi_i, i \in n$ along the desired path,
- the case variable $cs \in \{cs\_stopdistance, cs\_following, cs\_drive\}$,
- the desired velocity v_d
- the index i_f of the curve point representing the possible front,
- and the possible velocity v_{front} of the front.

A curve point ξ_i describes besides the position $(x, y)_i$ the direction ψ_i and the curvature κ_i at one spot of the planned curve $\vec{r}_c$ and provides all the information needed for lateral control.

$$\xi_i = (x, y, \psi, \kappa)_i^T \tag{1}$$

In the case of the discrete path planning algorithm, the curve points values are simply derived from the position, the orientation and the steering angle of the vehicle in each step.

B. Interpolation method

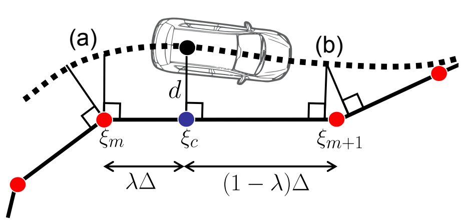

Fig. 3. Interpolation between curve points

After the information is transferred to low-level control, the deviation to the desired behavior needs to be determined via interpolation method taking into account the vehicle's current position (e. g. rear wheels center), orientation, and velocity (see Fig. 1).
As a good approximation of the geometries of the vehicle's projected position on the curve, ξ_c is introduced and can be calculated from

$$\xi_c = (x_c, y_c, \psi_c, \kappa_c)^T = \lambda\,\xi_m + (1-\lambda)\,\xi_{m+1} \tag{2}$$

with

$$\lambda = \frac{\left\langle \begin{bmatrix} x_{m+1} - x_m \\ y_{m+1} - y_m \end{bmatrix}, \begin{bmatrix} x - x_m \\ y - y_m \end{bmatrix} \right\rangle}{\left\| \begin{bmatrix} x_{m+1} - x_m \\ y_{m+1} - y_m \end{bmatrix} \right\|_2^2} \tag{3}$$

whereas ξ_m and ξ_{m+1} are the two closest curve points[1] to the vehicle's reference point.
In order to prevent extrapolations, λ needs to be saturated to values between 0 and 1. As a matter of fact, the calculated projected reference point on the desired path might get stuck (a) (see Fig. 3) or jump (b) if the lateral offset gets big, even though the vehicle moves continuously. For moderate distances between the curve points and small lateral deviations, as given during normal operation, these effects are completely negligible.

As the last two required quantities, the distance d_f from the projected position (x_c, y_c) to the front curve point is given by

$$\begin{aligned} d_f =& \sqrt{(x_{m+1} - x_c)^2 + (y_{m+1} - y_c)^2} \\ &+ \sum_{k=m+1}^{i_f} \sqrt{(x_{k+1} - x_k)^2 + (y_{k+1} - y_k)^2} \end{aligned} \tag{4}$$

and the signed lateral offset d (see Fig. 3) by

$$d = \left\| \begin{bmatrix} x - x_c \\ y - y_c \end{bmatrix} \right\|_2 \cdot \operatorname{sgn}\left(\det \begin{bmatrix} x_{m+1} - x_m & x - x_c \\ y_{m+1} - y_m & y - y_c \end{bmatrix} \right), \tag{5}$$

which forms a right handed system.

[1]assuming equidistant curve points

III. ORBITAL TRACKING CONTROLLER

Actually, the problem of stabilizing a vehicle along a given trajectory is a common example in flatness-based tracking control (see e. g. [2]), which combines lateral and longitudinal control in a single controller. However, separating lateral and longitudinal control, as mentioned in the beginning, has turned out to lead to a more robust and flexible overall system, especially in the integration phase.
And yet, the choice of the so-called *flat output* of the non-holonomic vehicle model, the position of the rear wheels center (x, y) (see Fig. 4), turns out to be also a well suited reference point for our purpose, as the vehicle and the tangent to the driven path of that point have always the same orientation.

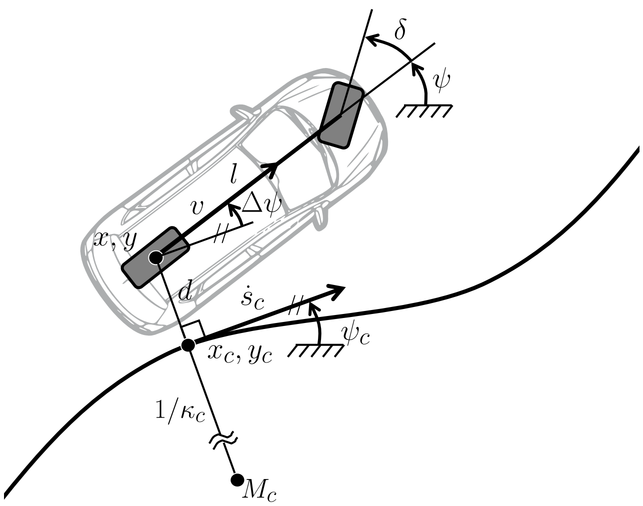

Fig. 4. Non-holonomic one track model

The dynamics of a non-holonomic vehicle (Fig. 4) in local coordinates s_c, d, and $\Delta\psi$ are given by

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} s_c \\ d \\ \Delta\psi \end{bmatrix} = \begin{bmatrix} \frac{\cos\Delta\psi}{1-d\kappa_c(s_c)} \\ \sin\Delta\psi \\ \frac{\tan\delta}{l} - \kappa_c(s_c)\frac{\cos\Delta\psi}{1-d\kappa_c(s_c)} \end{bmatrix} v, \quad (6)$$

whereas the steering wheel angel δ and the longitudinal velocity v is the system's input, d is the lateral offset to the path, $\Delta\psi$ is the angle between the vehicle and the tangent to the path, and l the distance between the rear and the front axle. The singularity at $1 - d\kappa_c(s_c) = 0$ is no restriction in practice since $d \ll \frac{1}{\kappa_c(s_c)}$. A proof of (6) can be found in the Appendix.

Since orbital tracking control does not have any time dependencies, (6) can be rewritten with the arc length s_c as the new time parametrization .
With $\frac{\mathrm{d}}{\mathrm{d}t}() = \frac{\mathrm{d}}{\mathrm{d}s_c}() \cdot \frac{\mathrm{d}s_c}{\mathrm{d}t}$ it becomes

$$\frac{\mathrm{d}}{\mathrm{d}s_c}\begin{bmatrix} s_c \\ d \\ \Delta\psi \end{bmatrix} = \begin{bmatrix} 1 \\ \sin\Delta\psi \cdot \frac{1-d\kappa_c(s_c)}{\cos\Delta\psi} \\ \frac{\tan\delta}{l} \cdot \frac{1-d\kappa_c(s_c)}{\cos\Delta\psi} - \kappa_c(s_c) \end{bmatrix}. \quad (7)$$

For small deviations d and $\Delta\psi$ from the desired curve and $\frac{\mathrm{d}}{\mathrm{d}s_c}() = ()'$, a partial linearization leads to

$$\begin{bmatrix} d \\ \Delta\psi \end{bmatrix}' = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} d \\ \Delta\psi \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \end{bmatrix}\kappa_c + \begin{bmatrix} 0 \\ \frac{1}{l} \end{bmatrix}\tan\delta. \quad (8)$$

The feedback linearizing control law

$$\delta = \arctan(-lk_0 d - lk_1\Delta\psi + l\kappa_c) \quad (9)$$
$$= \arctan(-k_1^\star d - k_2^\star\Delta\psi + l\kappa_c) \quad (10)$$

with $k_0, k_1 > 0$ yields the stable linear error dynamics

$$\frac{\mathrm{d}}{\mathrm{d}s_c}\begin{bmatrix} d \\ \Delta\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -k_0 & -k_1 \end{bmatrix}\begin{bmatrix} d \\ \Delta\psi \end{bmatrix} \quad (11)$$

with respect to s_c with the characteristic polynomial

$$\lambda^2 + k_1\lambda + k_0 = 0. \quad (12)$$

As long as

$$\dot{s}_c > 0, \quad (13)$$

the system is also stable with respect to time. For backward driving the signs of k_0 and k_1 have to be adjusted to the applied sign convention and yields exactly the same error dynamics as for forward driving.
Fig. 7 shows the transient behavior to different initial

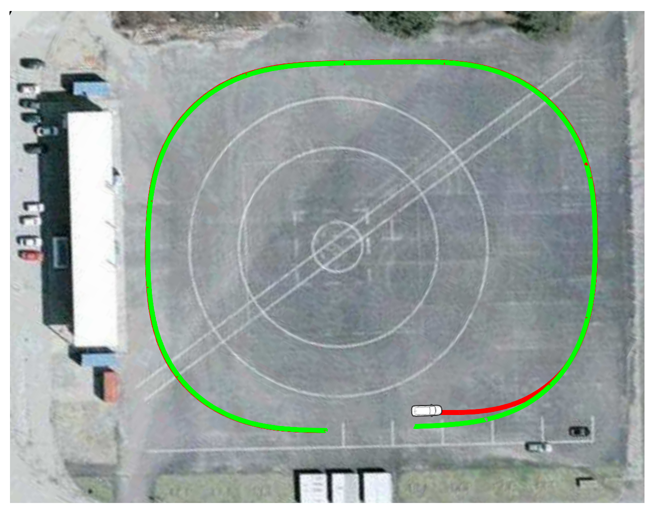

Fig. 5. Test circuit

errors $\Delta\psi$ and d for forward (blue) and backward driving (red) simulated with MATLAB/SIMULINK. As parameters for the simulation the Passat's axis distance $l = 2.72$, a maximum steering angle of $\delta_{\max} = 30°$, the controller parameters $k_0 = 0.25\,l$ and $k_1 = 1.25\,l$ and equidistant curve points with $\Delta = 2$m were chosen.
In Fig. 5 a real test run along with the corresponding measured data in Fig. 6 can be seen.
Obviously neither the input saturation $\delta_{\max}$ nor the discrete representation of the curve cause any significant problems.

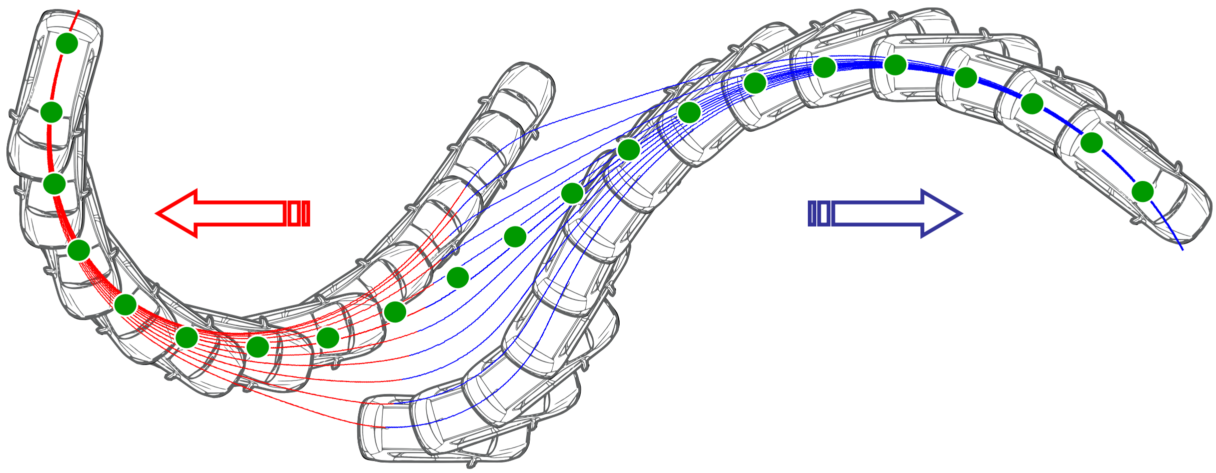

Fig. 7. Transient trajectories for different initial positions

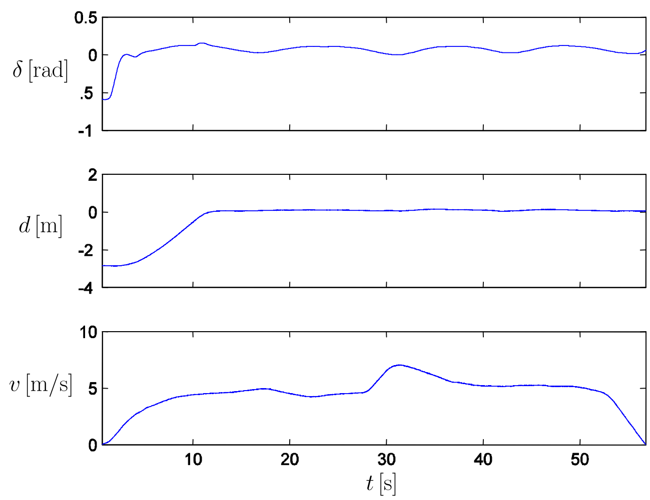

Fig. 6. Measured data to circuit test run

IV. Longitudinal controller system

A. Following controller

Since the acceleration of the leading vehicle is hard to determine, it is assumed that the vehicle keeps its velocity v_B constant. Choosing the distance d_f and its time derivative $\dot{d}_f$ as the state variables and AnnieWAY's acceleration $a_f = \dot{v}$ as the input, the system's dynamics are given by

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} d_f \\ \dot{d}_f \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} d_f \\ \dot{d}_f \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \end{bmatrix} a_f \tag{14}$$

As DARPA [1] requires the vehicle to maintain a minimum forward vehicle separation of one vehicle length minimum and one length for every additional 10 mph, the desired distance $d_{f,d}$ can be calculated by

$$d_{f,d} = d_{f,0} + \tau v \tag{15}$$

with the according parameters $d_{f,0}$ and τ. Considering the acceleration $\dot{v}_B$ of the leading vehicle an unmeasurable disturbance, the linear set-point control law

$$\begin{aligned} a_f &= c_0(d_f - d_{f,d}) + c_1\dot{d}_f & (16)\\ &= c_0(d_f - d_{f,d}) + c_1(v_B - v) & (17)\end{aligned}$$

and $v = v_B - \dot{d}_f$ yields the total system

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} d_f \\ \dot{d}_f \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -c_0 & -c_0\tau - c_1 \end{bmatrix}\begin{bmatrix} d_f \\ \dot{d}_f \end{bmatrix} + \begin{bmatrix} 0 \\ c_0(d_{f,0} + \tau v_B) \end{bmatrix} \tag{18}$$

$$= Ax + B$$

with the equilibrium position of the closed loop

$$\begin{aligned} x_{stat} &= -A^{-1}B \\ &= -\frac{1}{c_0}\begin{bmatrix} -c_0\tau - c_1 & -1 \\ c_0 & 0 \end{bmatrix}\begin{bmatrix} 0 \\ c_0(d_{f,0} + \tau v_B) \end{bmatrix} \\ &= \begin{bmatrix} d_{f,0} + \tau v_B \\ 0 \end{bmatrix} \end{aligned} \tag{19}$$

The characteristic polynomial can directly be read off from (18)

$$\lambda^2 + (c_0\tau + c_1)\lambda + c_0 = 0 \tag{20}$$

A double Eigenvalue $\lambda_{1/2} = -1$ leads to a pleasant an yet save following behavior.

B. Stopping controller

The following controller of the previous section leads to a behavior, which can best be described as *flowing with the traffic*. By contrast, the stopping controller should come to a controlled stop at a certain point as fast as possible without exceeding any comfort criteria. The control law

$$a_s = -\frac{v^2}{2(d_f - d_\Delta)} \tag{21}$$

leads to a constant deceleration until the vehicle is d_Δ away from the stop point. To prevent the controller from decelerating too soon and switching on and off, a hysteresis

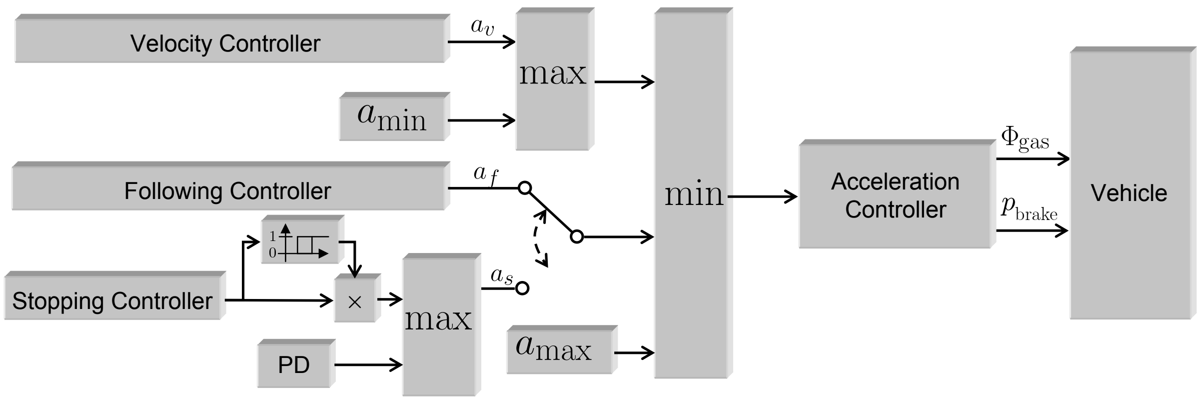

Fig. 8. Longitudinal override control strategy

with the thresholds $a_{s,max}$ and $a_{s,min}$, as shown in Fig. 8, is introduced. The singularity at $d_f = d_\Delta$ is avoided by a PD position controller that takes over via a min-operator and ensures a smooth and save stop at the end.

C. Velocity controller

As $\dot{v} = a$, the simple proportional velocity control law

$$a_v = -c_v(v - v_d) \tag{22}$$

stabilizes AnnieWAY's velocity v to the desired velocity v_d with a PT_1 behavior.

D. Override control strategy

All three previously introduced controllers are combined by an override control strategy depicted in Fig. 8. The bumpless transfer between velocity control and following/stopping control is assure by the max operator. Additional saturation, realized by $a_{\max}$ and $a_{\min}$, prevent the vehicle from inappropriately high acceleration or deceleration without reducing safety.

V. Conclusions

For autonomous vehicles an interface between high level decision making and low level control has been introduced, which handles all the maneuvers required in the *Urban Challenge 2007*. The interface comprises primarily of points representing the free section of the planned path. Via an interpolation method the lateral offset as well as the distance to the front can be determined and used for the lateral and longitudinal controller.

The suggested feedback-linearizing orbital tracking controller offers the advantage of a velocity independent transient behavior, especially suitable for narrow maneuvers at low and middle velocity.

For longitudinal control an override control strategy integrating different controllers for driving, stopping, and following has been described that lead in combination with the lateral controller to a quite natural and confident driving behavior in the competition.

VI. Acknowledgements

The authors gratefully acknowledge the collaboration of all partners from University of Karlsruhe (TH), Technical University of Munich (TUM), and University of the German Federal Armed Forces, Munich. This work would not have been possible without the ongoing research of the Transregional Collaborative Research Centre 28 *Cognitive Automobiles*. Both projects cross-fertilized each other and revealed significant synergy.

VII. Appendix

A. Mathematical model of the system

In a first step the relation between v and $\dot{s}_c$ has to be derived. Since the reference point $\vec{r}_c = (x_c, y_c)^T$ on the curve is the one with the shortest distance, the connection form this point to the rear axle middle point $\vec{r} = (x, y)^T$ and the tangent $\vec{t}_c$ of the curve form a right angle at all times (see Fig. 4), which can be written in the form

$$[\vec{r}(s(t)) - \vec{r}_c(s_c(t))]^T \, \vec{t}_c(s_c(t)) = 0$$

With the time derivative one gets

$$\left[\frac{\mathrm{d}\vec{r}}{\mathrm{d}s}\dot{s} - \frac{\mathrm{d}\vec{r}_c}{\mathrm{d}s_c}\dot{s}_c\right]^T \vec{t}_c + [\vec{r} - \vec{r}_c]^T \frac{\mathrm{d}\vec{t}_c}{\mathrm{d}s_c}\dot{s}_c = 0. \tag{23}$$

Using Frenet's Formula $\vec{t}_c^{\,\prime} = \kappa_c \vec{n}_c$ and

$$\vec{n}_c = \frac{\vec{r} - \vec{r}_c}{\|\vec{r} - \vec{r}_c\|_2} = \frac{\vec{r} - \vec{r}_c}{d},$$

(23) can be rewritten with $\dot{s} = v$ as

$$\begin{aligned}
[\vec{t}v - \vec{t}_c\dot{s}_c]^T\vec{t}_c - \kappa_c d\dot{s}_c &= 0 \\
(\cos\psi\cos\psi_c + \sin\psi\sin\psi_c)v - \dot{s}_c - \kappa_c d\dot{s}_c &= 0 \\
\cos(\psi - \psi_c)v - \dot{s}_c - \kappa_c d\dot{s}_c &= 0
\end{aligned}$$

which yields the relation

$$\dot{s}_c = \frac{\cos\Delta\psi}{1 - d\kappa_c}v.$$

The time derivative of

$$d^2 = [\vec{r}(s) - \vec{r}_c(s_c)]^T[\vec{r}(s) - \vec{r}(s_c)]$$

yields

$$
\begin{aligned}
2d\dot{d} &= 2[\vec{r} - \vec{r}_c]^T[\vec{t}v - \vec{t}_c\dot{s}_c] \\
&= 2d\vec{n}_c^T[\vec{t}v - \vec{t}_c\dot{s}_c] \\
\dot{d} &= \vec{n}_c^T\vec{t}v \\
&= (\cos\psi_c \sin\psi + \sin\psi_c \cos\psi)v \\
&= \sin(\psi - \psi_c)v = v\sin\Delta\psi
\end{aligned}
$$

Differentiating $\Delta\psi$ becomes

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}\Delta\psi &= \frac{\mathrm{d}}{\mathrm{d}t}(\psi - \psi_c) = \dot{\psi} - \frac{\mathrm{d}\psi_c}{\mathrm{d}s}\dot{s}_c = \frac{\tan\delta}{l}v - \kappa_c\dot{s}_c \\
&= \frac{\tan\delta}{l}v - \kappa_c\frac{\cos\Delta\psi}{1 - d\kappa_c}v.
\end{aligned}
$$

Thus, the non-holonomic dynamics in local coordinates are given by (6).

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