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Appendix A

Appendix

The appendix provides additional information and outlines further ideas that are not part of the core of this thesis or are only mentioned briefly in the outlook of Section 6.3.

A.1 Applicability to a Conventional Vehicle

This section sketches possible ways to apply the proposed approach for reactive obstacle avoidance to conventional cars that are not able to independently actuate the lateral and longitudinal velocity.

Longitudinal Control: The simplest way is the limitation of the lateral velocity v_Y to zero so that the optimization output is only a longitudinal velocity change. Despite this restriction, the scheme is not a mere braking assistant as the vehicle can choose between accelerating and braking to anticipate and avoid collisions.

Input for a Cartesian planer: In the original scheme, the output of the optimizer is a change of the velocities. Considering that the velocity change is applied immediately at the current position ξ_t, the vehicle will move to a certain position $\xi_{(t+TTC)}$ until the camera plane meets the observed object.

$$\xi_{(t+TTC)} = \xi_t + \begin{pmatrix} \Delta X \\ \Delta Y \end{pmatrix} \tag{A.1}$$

The distance to $\xi_{(t+TTC)}$ in the vehicle's original X and Y coordinates can be determined as:

$$\begin{pmatrix} \Delta X \\ \Delta Y \end{pmatrix} = \begin{pmatrix} v_X + \Delta v_X \\ v_Y + \Delta v_Y \end{pmatrix} TTC \; \Delta t \tag{A.2}$$

Now, the point $\xi_{(t+TTC)}$ can be set as goal point for a motion planning algorithm. For instance, a clothoid could be planned to reach this point and a velocity profile must be calculated to ensure getting there in time.

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A.2 Utilization of the Essential Matrix

A further interesting open point is whether the Essential Matrix principle could be utilized in an approach similar to the Direct Homography Control from Section 3.3.3 that exploits the homography principle. Initially, the homography matrix was derived for planar motions only (3.72) so that the state vector ξ is three dimensional. When applying the same procedure to the essential matrix (3.9), it also becomes a function of α and time-variant:

$$\mathbf{E}(\alpha, t) = \begin{pmatrix} -t_2\sin(\alpha) & -t_3 & -t_2\cos(\alpha) \\ t_3\cos(\alpha) + t_1\sin(\alpha) & 0 & t_3\sin(\alpha) - t_1\cos(\alpha) \\ -t_2\cos(\alpha) & t_1 & -t_2\sin(\alpha) \end{pmatrix} \tag{A.3}$$

Note, that the variables and notations are taken from Section 3.3.3 and hence not explained again. In the next step, the relation between position changes and changes of the entries of the essential matrix are expressed by a Jacobian matrix $\mathbf{J}_E$, which is obtained by combining the vector of stacked entries of $\mathbf{E}$ and the time derivative of (3.73):

$$\dot{\mathbf{h}}_E = \mathbf{J}_E(\alpha)\frac{\delta\xi}{\delta t} \tag{A.4}$$

Determining the derivatives explicitly leads to the following equation that is the essential matrix's equivalent to (3.77):

$$\dot{\mathbf{h}}_E = \begin{pmatrix} 0 & 0 & -t_2\cos(\alpha) \\ -1 & 0 & 0 \\ 0 & 0 & -t_2\sin(\alpha) \\ \cos(\alpha) & \sin(\alpha) & t_1\cos(\alpha) - t_3\sin(\alpha) \\ 0 & 0 & 0 \\ \sin(\alpha) & -\cos(\alpha) & t_3\cos(\alpha) + t_1\sin(\alpha) \\ 0 & 0 & t_2\sin(\alpha) \\ 0 & 1 & 0 \\ 0 & 0 & -t_2\cos(\alpha) \end{pmatrix} \begin{pmatrix} v_X \\ v_Y \\ \dot{\psi} \end{pmatrix} \tag{A.5}$$

At first sight, it can be seen that $\mathbf{J}_E$ requires not only the current α state but also the states t_1 and t_3, so that a linearization or 'a priori' state estimation becomes necessary, which questions the applicability and the possible benefit of this approach. However, it has to be examined if a better formulation for the correlation between velocity changes and the changes of the entries of $\mathbf{E}$ exists. Another open question is whether the scale has to be induced for a stable controller. Probably, it is not necessary, as the scale for the DHC is provided by the d term, which does not have to be known accurately for the controller but for the position estimation. Moreover, other examples can be found in the field of image-based visual servoing, where the depth is only coarsely estimated or set to a unit value - see Section 2.3.2.

A.3 Car-2-X-Aided Visual Platooning

The vision-based platooning approach of Section 3.3.3.3 can definitely profit by adding a Car-2-X connection to the scheme. Different issues can be solved elegantly by the additional information that can be provided via Car-2-X, as for example:

- The target view including a template or feature points together with distance d and normal vector $\mathbf{n}$.

- The position of the preceding vehicle PV in global coordinates.

- The current $\mathbf{u}_{(PV,t)}$ and predicted motion state $\mathbf{u}_{(PV,t+n)}$.

A common question of all vision-based control approaches is: how can the target view (or target feature points etc.) be made available to the robot. Often the target is taught in an earlier run or is simply considered as known. Therefore, the transmission via Car-2-X from the preceding vehicle, which should know how it 'looks', is a very convenient way for the platooning task. If possible, the values for d and $\mathbf{n}$ should be also provided, since exact values improve the performance of the DHC position estimation. One of the advantages of the homography principle is that distance, direction, and target view have to be transmitted only once, except if the goal position changes. This could be for example necessary if the following distance has to be increased. However, it should be no problem for a preceding vehicle to have a set of different target views available together with the corresponding $\mathbf{n}$ and d values to define different goal poses for the following vehicle.
A further very valuable information is the global position of the preceding vehicle. On the one hand the α estimation of the controller and the position estimation, which is needed for the motion state estimation of PV, can be improved by fusion if the own position in the global coordinate system is also available. On the other hand the position information can already be utilized in the vision part that determines the Homography matrix. It will increase the efficiency and robustness of the matching algorithm, if the image region is known in which the target is expected.
As written in Section 3.3.3.3, an estimate of PV's motion state is vital to stick to the preceding vehicle in case that it is driving demanding maneuvers with fast motion and direction changes. A constant update of PV's state and especially information about its intention can definitely improve the robustness of the controller.
Furthermore, a whole platooning service could be established based on this scheme using vision-based platooning with Car-2-X. Let us consider a driver on a highway who wants to change to platooning mode. Therefore, she first sends a request via a Car-2-X broadcast including the planned route. Another vehicle, which plans to use at least a part of the same route, answers and offers to guide the car during the common route. After accepting this offer, the target view and parameters are transmitted and a direct Car-2-X connection is established to send continuously position and velocity information.
Moreover, it is also possible that the DHC position estimation could be part of a platooning scheme as described in [11]. Even if the controllers for the lateral and longitudinal vehicle position work in Cartesian space, the DHC-PEα can be utilized to determine the current relative position to the preceding vehicle. Additionally to the visual feedback, a Car-2-X signal from the preceding vehicle is received that contains its GNSS coordinates. Therefore, the position-estimation can be fused with the Car-2-X information to obtain a better result.

A.4 Tentacle Tree - Hybrid Motion Planning for the ROMO

Motion planning for the ROMO is an especially challenging task due to the three different motion-control modes - compare Section 4.5. Planning a maneuver incorporating more then only one motion mode can be done either by a fixed sequence of motion modes as for the parking example of Section 4.5.2 or the system has to be considered as a hybrid system that is described by continuous equations (the motion model) that vary in different discrete states (motion modes).
Planning with motion primitives is a frequently used technique for mobile robots to handle a high dimensional state space. One example is the tentacle approach from [299] that is designed for reactive planning of an autonomous vehicles in unstructured environments. The so-called tentacles are drive-able motion primitives that are chosen according to the vehicle's current state (velocity and steering angle). The set of tentacles is then projected into an occupancy grid map representation that contains the surrounding obstacles so that the best tentacles can be selected according to different criteria like the maximal clearance. Finally, the next i control inputs are derived from the chosen tentacle. Even though only i control inputs are derived, the evaluated tentacle is much longer to prevent reaching insecure states.
This concept of motion primitives is extended here in a way that not only the next tentacle is selected, but a planning horizon of n steps is used. This means that the vehicle state is predicted after applying the i control inputs and a node point is set. It is also possible that more than one node is set as more than one motion primitive may be valid. After all options have been evaluated, the procedure starts again by checking the currently available sets at each node of the preceding layer to create a new layer of nodes. This procedure is repeated n times, which denotes the depth of the tree-like structure that is now called Tentacle Tree (TT) consisting of nodes connected by motion primitives. This complex structure increases the computational effort but is necessary to build a planer that is able to plan a path with an arbitrary number of mode changes for an arbitrary sequence of modes. This was not the case for the parking example as shown in Figure 4.12, which could be solved by two mode changes in a fixed sequence.

The basic principle of the TT is now described by an artificial example depicted in Figure A.1. The ROMO starts in a narrow maze at pose P_0 and tries to reach the goal pose P^*, while the structure of the maze is known from a map. The initial mode is the longitudinal one, denoted by a blue trajectory, and the initial v_X is positive so that the ROMO has only the possibility to drive straightforward. During the planning the ROMO recognizes that it is not possible to continue with the same velocity in the longitudinal mode and the velocity is decreased until standstill is reached at P_2. The zero velocity enables mode changes and new tentacle primitives become available. Now, the lateral mode is chosen as only possible option and kept until the narrow passage widens. A zero velocity is planned for P_6, which enables also rotations. The rotational mode is an exception as it (mainly) does not provide own tentacles but enables a great variety of new primitives for both other modes. The planner chooses then a 180° rotation in combination with the longitudinal mode that is kept until P^* is reached. Note, that this example is

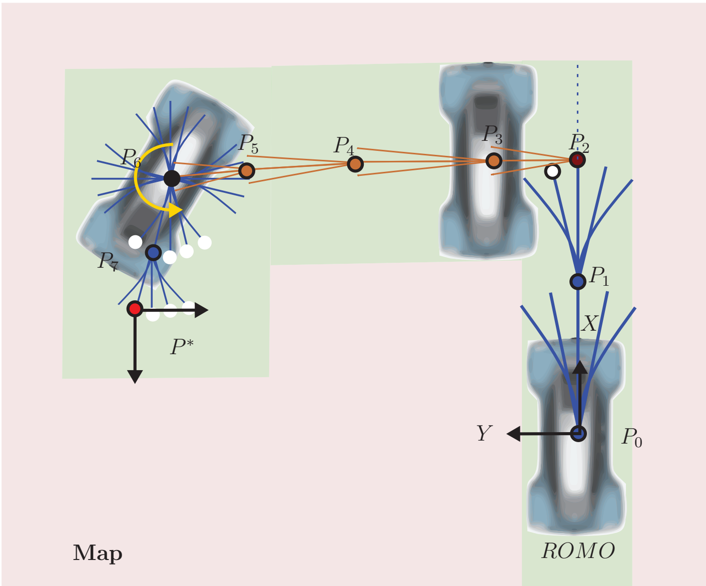

Figure A.1: Function principle of the Tentacle Tree.

simplified and almost only nodes are depicted in Figure A.1 that are part of the final path. The existence of discarded nodes (white) and tentacles is only indicated for the ease of understanding. An efficient pruning/selection of nodes is vital for the applicability of the method and is only one among different other issues that have to be tackled:

- A **set of motion primitives** has to be created to cover the state space for all three modes efficiently.
- Another vital task is to set up an **intelligent strategy to build up the tentacle tree** and to prune it concurrently. Nodes have to be evaluated if they should be eliminated and the number of admissible nodes must be limited for each layer, while the limit should decrease for higher layers.
- The **search algorithm** for the TT has to be developed (or selected) to find the optimal path.
- The **drive-ability** of the selected path must be ensured especially for narrow or critical passages.
- A **cost-function** has to be set up to assign costs to all transitions and nodes.
- Rules or guidelines for the **parametrization** have to be found: How many steps should be considered? What is the minimal and maximal number of primitives for each mode? etc.

On the one hand there are many open tasks, but on the other hand the TT approach has various potential advantages:

- It can **exploit the entire high maneuverability** of the ROboMObil by considering its hybrid character explicitly.
- Due to pre-calculations and discretization, the TT has the potential for **online planning**.
- **Constraints** can be taken easily into consideration by neglecting infeasible primitives.
- It is possible to set **different optimization goals**. Not only values for duration, energy efficiency etc. can be stored in the primitive descriptions, but also a function for trajectory tracking can be integrated.
- The TT representation has also the possibility to consider explicitly **dynamic obstacles** by predicting their positions over time.

All in all, this approach could be a good choice for a hybrid motion planner for the ROboMObil, as it has the potential to plan a path with an arbitrary number and sequence of motion modes while being still potentially real-time capable. However, there are different open issues that require further research and/or parametrization.

Symbols and Mathematical Notation

Notation/Symbol	Description	Dimension	Unit
x	Scalar variable	1	-
$\mathbf{x}$	Vector - Lower case and bolt	$n > 1$	-
$\mathbf{X}$	Matrix - Capital bolt letter	$n \times m,\ n, m > 1$	-
x_y	Specific value x belonging to an entity y	-	-
$x_{(y,t)}$	Specific value x belonging to an entity y at time step t	-	-
$\hat{x}$	Estimated value of x	-	-
$\dot{x}$	Time derivative of x	-	-
Δx	A difference of x	-	-
ϵ_x	Error term regarding x	-	-
$\underline{\mathbf{x}/\mathbf{X}}$	Reduced version of vector/Matrix $\mathbf{x}/\mathbf{X}$	-	-
$\underline{\underline{\mathbf{x}/\mathbf{X}}}$	Twice reduced version of vector/Matrix $\mathbf{x}/\mathbf{X}$	-	-
a_p, b_p, c_p	Distances from an image point p to o_y in different frames	1	$[pix]$
a_X, a_Y	Acceleration in X or Y direction	1	$[m/s^2]$
$\mathcal{A}, \mathcal{B}$	Parameter sets	-	-
C	A camera	-	-
c	Coverage of an object by its cluster	1	-
d	A distance in Cartesian or Image space	1	$[m]$ or $[pix]$
e_p	Epipolar line corresponding to the relative motion to $\mathbf{P}$	-	-
$\mathbf{e}_{(.,.)}$	Epipole in an image I	$\mathbb{R}^2$	-
$\mathbf{E}$	Essential matrix	3×3	-
$\mathbf{e}_G$	Global Epipole	2	$[pix]$
$\mathbf{e}_\Omega$	Epipole of cluster/object Ω	2	$[pix]$
fps	Frames per second	1	$[1/s]$
$\mathbf{f}$	Focal length	2	$[m]$
fs_x, fs_y	Focal length	1	$[pix]$
$\mathbf{f}(), \mathbf{g}()$	Exemplary (multi-) variable function	-	-
$\underline{\mathbf{G}}$	List of matched feature points/optical flow vectors	-	-
$\mathbf{G}$	Filtered list of matched points/optical flow vectors	-	-

Table A.1: List of mathematical notations and symbols - Part I.

A. Schaub, *Robust Perception from Optical Sensors for Reactive Behaviors in Autonomous Robotic Vehicles*, DOI 10.1007/978-3-658-19087-3

Notation/Symbol	Description	Dimension	Unit
$\mathbf{g}$	Optical flow vector in an image	-	-
g, q	shaping parameter for ω_{TTC}	1	-
H	Height of the camera above ground	1	$[m]$
$\mathbf{H}$	Homography matrix	3×3	-
$h_{p,q}$	Distance to optical axis of the camera in Y_C	1	$[m]$
I	A camera image	-	-
J	Cost function	1	-
$\mathbf{J}$	Jacobi matrix for the DHC	9×3	-
k	Shaping parameter of a cluster's cost-function term	1	-
l	A length in Cartesian or Image space	1	$[m]$ / $[pix]$
m, n, j	A number or quantity	1	-
$\mathbf{n}$	Normal vector in Cartesian or Image space	3 / 2	$[m]$ / $[pix]$
$\mathbf{n}_{\breve{\Omega}}$	Number of cluster fractions belonging to an object	1	-
$\underline{\widetilde{\mathbf{O}}}_t$	Set of all clusters $\underline{\widetilde{\mathbf{o}}}_{k,t}$	-	-
$\widetilde{\mathbf{O}}_t$	Set of merged clusters	-	-
$\underline{\mathbf{O}}_t$	Set of merged clusters with determined epipoles	-	-
$\mathbf{O}_t$	final set of clusters	-	-
$\mathbf{O}$	Optical center of a camera in Cartesian coordinates	3	$[m]$
$\mathbf{o}$	Optical center of a camera in image coordinates u, v	2	$[pix]$
$\mathbf{P}, \mathbf{Q}$	Cartesian points	3	$[m]$
$\mathbf{p}, \mathbf{q}$	Projected image point of $\mathbf{P}$ or $\mathbf{Q}$	2	$[pix]$
$\mathbf{p}, \mathbf{q}_{(c,.)}$	Homogenous image points	3	$[pix]$
$\mathbb{P}$	Set of feature points	-	-
$\mathbf{R}$	Rotation matrix	$\mathbb{R}^{3x3}$	-
$\mathbf{s}$	Start value for the ALIS search	2	-
$(S)TTC$	(Single point) Time-To-Collision value	1	[frames]
$\mathbf{t}$	Translation vector	$\mathbb{R}^3$	-
t	Time or time-step	1	$[s]$ or -
t_{TTC}	Time-To-Collision value	1	$[s]$
Δt	Time between two images	1	$[s]$
u, v / x, y	Image coordinates	1	$[pix]$
$\mathbf{u}$	Motion control interface to the actuator layer/VDC	3 / -	-
$\mathbf{v}$	Relative velocity vector	2	$[m/s]$
$\mathbf{v}_C$	The camera's velocity vector	2	$[m/s]$
$\mathbf{v}_O$	Object O's velocity vector	2	$[m/s]$
w_i	A parameter for determining a weight or shape of a cost-function	1	-
$\mathbf{x}_p$	image coordinates $[x, y]$	2	$[pix]$
$\mathbf{x}_{(P,c,.)}$	Homogenous image coordinates for a point P	$\mathbb{R}^3$	$[pix]$
$\mathbf{X}_{(P,.)}$	Spatial coordinates for a point P	$\mathbb{R}^4$	$[m]$
X, Y, Z	Cartesian vehicle coordinates	1	$[m]$
X_C, Y_C, Z_C	Cartesian camera coordinates	1	$[m]$
$X_{(TTC)}$	X coordinate in TTC map	1	-

Table A.2: List of mathematical notations and symbols - Part II.

Notation/Symbol	Description	Dimension	Unit
α	Ratio between v_X and v_Y	1	-
β	Side-slip angle	1	$[rad]$
χ	Cartesian coordinate system with the elements $[X, Y, Z]$	$\mathbb{R}^3$	-
χ_0	World frame (Cartesian coordinate system)	$\mathbb{R}^3$	-
$\chi_{(c)}$	Homogenous χ with the elements $[X, Y, Z, 1]$	$\mathbb{R}^4$	-
χ_u, χ_l	Left and right vertical boundary of a cluster	1	$[pix]$
δ_q	Distance between $\mathbf{e}_q$ to o_y	1	$[pix]$
ϵ	A noise/error term	n	[.]
η	Step size for ALIS	1	-
λ	Scalar parameter	1	$[m]$ / -
μ_i	Mean value of i	-	-
ν	distance limit in the clustering	1	$[pix]$
ν_i	Noise value added/multiplied to size i	-	-
ω	A weighting term	1	-
Ω	An object or obstacle	-	-
Π	Planar surface	-	-
ϕ	Orientation	1	$[°]$
$\dot{\psi}$	Yaw rate	1	$[rad/s]$
ρ	Curvature	1	$[1/m]$
σ_i	Standard deviation of i	-	-
Υ	ALIS search interval	-	-
ξ	Pose in a local or global Cartesian coordinate system	3	$[m, m, rad]$
ζ	Vehicle inner-loop dynamics	-	-

Table A.3: List of mathematical notations and symbols - Part III.

List of Abbreviations

Abbreviation	Description
$2D, 3D$	Two dimensional/dimensions, Three dimensional/dimensions
ADAS	Advanced Driver Assistance System
AI	Artificial Intelligence
AIA	Artificial Intelligence Agent
AKAZE	Accelerated-Kaze features
ALIS	Adaptive Lagrange Interpolation Search
AVG	AVeraGe value
BRISK	Binary Robust Invariant Scalable Keypoints
Car-2-X	Car to infrastructure or car to car communication
CAN	Controller Area Network
CAD	Computer Aided Design
DARPA	Defense Advanced Research Projects Agency
DLR	Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center
DOF	Degrees Of Freedom
DGPS	Differential Global Positioning System
DHC	Direct Homography Control
DHC-PE	DHC - Position Estimation without estimating the angular deviation.
DHC-PEα	DHC - Position Estimation with estimating the angular deviation.
EKF	Extended Kalman Filter

Table A.4: List of Abbreviations in alphabetical order - Part I.

A. Schaub, *Robust Perception from Optical Sensors for Reactive Behaviors in Autonomous Robotic Vehicles*, DOI 10.1007/978-3-658-19087-3

Abbreviation	Description
FAST	Features from Accelerated Segment Test
FOC	Focus Of Contraction
FOE	Focus Of Expansion
fov	field-of-view
FPGA	Field Programmable Gate Array
fps	frames per second
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMI	Human Machine Interface
HIL	Hardware-In-the-Loop
HSV	Hue, Saturation, Value (color coding)
IBVS	Image-based Visual Servoing
ICR	Instantaneous Center of Rotation
IMU	Inertial Measurement Unit
LIDAR	Light Detection And Ranging
KLT	Kanade-Lucas-Tomasi (Tracker)
MAV	Micro Air Vehicle
MPC	Model Predictive Control
NLG	Non-Linear Gradient descent
PBVS	Position-Based Visual Servoing
PV	Preceding Vehicle
RADAR	RAdio Detection And Ranging
RGB	Red, Green, Blue (color coding)
ROMO	ROboMObil
SGM	Semi-Global Matching
SI	Systeme international d'unites
SIFT	Scale-Invariant Feature Transform
SIL	Software-in-the-Loop
SLAM	Simultaneous Localization and Mapping
SONAR	SOund Navigation And Ranging
SPVE	Single point Velocity Estimation

Table A.5: List of Abbreviations in alphabetical order - Part II.

Abbreviation	Description
SQP	Sequential Quadratic Programming
SSVE	Sparse Stereo for Velocity Estimation
STTC	Single point Time-To-Collision/Contact
SURF	Speeded Up Robust Features
TT	Tentacle Tree
TTC	Time-To-Collision/Contact
UAV	Unmanned Aerial Vehicle
UKF	Unscented Kalman Filter
VDC	Vehicle Dynamics Controller

Table A.6: List of Abbreviations in alphabetical order - Part III.