Appendix A
The Modified Anderson-Björck-King Method

As presented in Chap. 4.2.1 (p. 50), the method of Anderson and Björck [12] with the improvement of King [131] is applied in this work. In order to improve the robustness (at the expense of efficiency), this method was combined with the bisection method as will be described in this appendix.

The Anderson-Björck-King method is a variant of the *regula falsi* and an improvement of the *Pegasus method* [70, 71]. We assume the function f to be continuous in the closed interval $[a, b]$ and that $f(a)f(b) < 0$. Hence, we know that there is at least one root of odd order within the interval of $]a, b[$. The Anderson-Björck-King method calculates one of these zeros by a repeated minimization of the root inclusion interval; it always converges if initially $f(a)f(b) < 0$.

The regarded functions f in the context of OTG can be of very different characteristics, which depend on the input values $\mathbf{W}_i$ at an instant T_i. Although we can always determine an interval $[a, b]$, from which we know that it contains the desired root x_0, it may happen that a (in contrast to the interval width) relatively large part of the function lies in parallel to the abscissa. Such functions lead to efficiency problems when applying the Anderson-Björck-King method, and in the worst case, the method will converge very slowly, such that we are not able to specify a worst-case execution time of the algorithm. To bypass this problem, to improve the robustness, and to be able to specify a maximum number of required iterations in order to be real-time capable, we combine the Anderson-Björck-King method with the simple bisection method. The first three steps of the following algorithm belong to the bisection method and all following ones to the Anderson-Björck-King method.

Given: $f : [a, b] \xrightarrow{cont} \mathbb{R}$, $f(a)f(b) < 0$, and an error threshold $\varepsilon > 0$ with $\varepsilon \in \mathbb{R}$.

Task: Find an approximation of one root $x_0 \in]a, b[$, such that the difference between the last two iterated values is smaller than ε.

Start: Take $x_1 := a$, $x_2 := b$ as initial values and compute $f_1 := f(x_1)$, $f_2 := f(x_2)$.

The iteration consists of the following seven steps:

1. Bisection Step

$$x_3 := \frac{x_1 + x_2}{2} \tag{A.1}$$

2. Calculation Step I

$$f_3 := f(x_3) \tag{A.2}$$

If $f_3 = 0$, the method ends with $x_0 = x_3$.

3. Interval Determination Step I

Determine a new inclusion interval: If $f_3 f_2 < 0$, x_0 lies between x_2 and x_3, and we set:

$$x_1 := x_2 \tag{A.3}$$
$$x_2 := x_3 \tag{A.4}$$
$$f_1 := f_2 \tag{A.5}$$
$$f_2 := f_3 \; . \tag{A.6}$$

If $f_3 f_2 > 0$ (x_0 lies between x_1 and x_3), we set

$$x_2 := x_3 \tag{A.7}$$
$$f_2 := f_3 \; . \tag{A.8}$$

4. Secant Step

Compute the slope of the connecting line from (x_1, f_1) to (x_2, f_2):

$$s_{12} = \frac{f_1 - f_2}{x_1 - x_2} \tag{A.9}$$

and set

$$x_3 := x_2 - \frac{f_2}{s_{12}} \; . \tag{A.10}$$

5. Calculation Step II

$$f_3 := f(x_3) \tag{A.11}$$

If $f_3 = 0$, the method ends with $x_0 = x_3$.

6. Interval Determination Step II

Determine a new inclusion interval: If $f_3 f_2 < 0$, x_0 lies between x_2 and x_3, and we set:

$$x_1 := x_2 \tag{A.12}$$
$$x_2 := x_3 \tag{A.13}$$
$$f_1 := f_2 \tag{A.14}$$
$$f_2 := f_3 \ . \tag{A.15}$$

If $f_3 f_2 > 0$ (x_0 lies between x_1 and x_3), we assign a new functional value at x_1:

If $1 - \frac{f_3}{f_2} \leq 0$, take

$$g := 0.5 \tag{A.16}$$

otherwise use

$$g := 1 - \frac{f_3}{f_2} \ . \tag{A.17}$$

Then set

$$x_2 := x_3 \tag{A.18}$$
$$f_1 := g f_1 \tag{A.19}$$
$$f_2 := f_3 \ . \tag{A.20}$$

7. Stop Condition Step

If $|x_2 - x_1| \leq \varepsilon$, stop the iteration.[1] If $|f_2| \leq |f_1|$ then set

$$x_0 := x_2 \tag{A.21}$$

otherwise

$$x_0 := x_1 \ . \tag{A.22}$$

If $|x_2 - x_1| > \varepsilon$, the iteration is continued with Step 1 with the new values x_1, x_2, f_1, and f_2 from Step 6.

Further details and an explanation with geometric interpretation of the Anderson-Björck-King method can be found in the book of Engeln-Müllges and Uhlig [73] and of course in [12, 131]. The original Anderson-Björck-King method is the most efficient numerical inclusion method regarding the efficiency index of Traub [264].

[1] For practical implementation, an error threshold of $\varepsilon = 10^{-12}$ was applied.

Appendix B
Details on the *PosTriNegTri* Acceleration Profile (Step 1)

B.1 Position-Error Function

Written form of the position-error function for the Step 1 *PosTriNegTri* acceleration profile:

$$
\begin{aligned}
{}^{PosTriNegTri}p_i^{err1}\left(a_i^{peak1}\right) = \frac{1}{12\;\left(J_i^{max}\right)^2}\Bigg(&4\left(A_i\right)^3 - 12\left(A_i\right)\left(J_i^{max}\right)V_i - 3\left(A_i\right)^2 \\
&\left(4\left(a_i^{peak1}\right) + \sqrt{-2\left(A_i\right)^2 + 4\left(a_i^{peak1}\right)^2 + 4\left(J_i^{max}\right)\left(V_i - V_i^{trgt}\right)}\right) \\
&+6\Bigg(2\left(a_i^{peak1}\right)^3 + 4\left(a_i^{peak1}\right)\left(J_i^{max}\right)V_i + \left(J_i^{max}\right)\Bigg(2\left(J_i^{max}\right)\left(P_i - P_i^{trgt}\right) + \left(V_i + V_i^{trgt}\right) \\
&\sqrt{-2\left(A_i\right)^2 + 4\left(a_i^{peak1}\right)^2 + 4\left(J_i^{max}\right)\left(V_i - V_i^{trgt}\right)}\Bigg) \\
&+\left(a_i^{peak1}\right)^2\sqrt{-2\left(A_i\right)^2 + 4\left(\left(a_i^{peak1}\right)^2 + \left(J_i^{max}\right)\left(V_i - V_i^{trgt}\right)\right)}\Bigg)\Bigg) .
\end{aligned}
$$

B.2 Derivative of the Position-Error Function

Written form of the derivative of the position-error function for the *PosTriNegTri* acceleration profile:

$$
\begin{aligned}
{}^{PosTriNegTri}p_i^{err1\prime}\left(a_i^{peak1}\right) = \Bigg(&6\left(a_i^{peak1}\right)^3 + 6\left(a_i^{peak1}\right)\left(J_i^{max}\right)V_i - 2\left(a_i^{peak1}\right) \\
&\left(J_i^{max}\right)V_i^{trgt} + 3\left(a_i^{peak1}\right)^2\sqrt{-2\left(A_i\right)^2 + 4\left(a_i^{peak1}\right)^2 + 4\left(J_i^{max}\right)\left(V_i - V_i^{trgt}\right)} \\
&+2\left(J_i^{max}\right)V_i\sqrt{-2\left(A_i\right)^2 + 4\left(a_i^{peak1}\right)^2 + 4\left(J_i^{max}\right)\left(V_i - V_i^{trgt}\right)}
\end{aligned}
$$

$$+ (A_i)^2 \left(-3 \left(a_i^{peak1} \right) - \sqrt{-2 (A_i)^2 + 4 \left(a_i^{peak1} \right)^2 + 4 (J_i^{max}) \left(V_i - V_i^{trgt} \right)} \right) \Bigg)$$

$$/ \left((J_i^{max})^2 \sqrt{-2 (A_i)^2 + 4 \left(a_i^{peak1} \right)^2 + 4 (J_i^{max}) \left(V_i - V_i^{trgt} \right)} \right) .$$

B.3 Setting up the Parameters of $\mathcal{M}_i$

This appendix section details the parameter calculation of $\mathcal{M}_i$ of Chap. 4.2.1 (p. 58). We first repeat the system of eqns. (4.21) – (4.32), which are required as a base for the following calculations. The unknown variables are t_i^{min}, ${}^2t_i$, ${}^3t_i$, ${}^4t_i$, ${}^2v_i$, ${}^3v_i$, ${}^4v_i$, ${}^2p_i$, ${}^3p_i$, ${}^4p_i$, a_i^{peak1}, and a_i^{peak2}.

$${}^2t_i - T_i = \frac{\left(a^{peak1} - A_i\right)}{J_i^{max}} \tag{B.1}$$

$${}^3t_i - {}^2t_i = \frac{a^{peak1}}{J_i^{max}} \tag{B.2}$$

$${}^4t_i - {}^3t_i = -\frac{a^{peak2}}{J_i^{max}} \tag{B.3}$$

$$t_i^{min} - {}^4t_i = -\frac{a^{peak2}}{J_i^{max}} \tag{B.4}$$

$${}^2v_i - V_i = \frac{1}{2} \left({}^2t_i - T_i\right) \left(A_i + a^{peak1}\right) \tag{B.5}$$

$${}^3v_i - {}^2v_i = \frac{1}{2} \left({}^3t_i - {}^2t_i\right) a^{peak1} \tag{B.6}$$

$${}^4v_i - {}^3v_i = \frac{1}{2} \left({}^4t_i - {}^3t_i\right) a^{peak2} \tag{B.7}$$

$$V_i^{trgt} - {}^4v_i = \frac{1}{2} \left(t_i^{min} - {}^4t_i\right) a^{peak2} \tag{B.8}$$

$$\begin{aligned} {}^2p_i - P_i = {} & V_i \left({}^2t_i - T_i\right) + \frac{1}{2} A_i \left({}^2t_i - T_i\right)^2 \\ & + \frac{1}{6} J_i^{max} \left({}^2t_i - T_i\right)^3 \end{aligned} \tag{B.9}$$

$$\begin{aligned} {}^3p_i - {}^2p_i = {} & {}^2v_i \left({}^3t_i - {}^2t_i\right) + \frac{1}{2} a^{peak1} \left({}^3t_i - {}^2t_i\right)^2 \\ & - \frac{1}{6} J_i^{max} \left({}^3t_i - {}^2t_i\right)^3 \end{aligned} \tag{B.10}$$

$${}^4p_i - {}^3p_i = {}^3v_i \left({}^4t_i - {}^3t_i\right) - \frac{1}{6} J_i^{max} \left({}^4t_i - {}^3t_i\right)^3 \tag{B.11}$$

$$\begin{aligned} P_i^{trgt} - {}^4p_i = {} & {}^4v_i \left(t_i^{min} - {}^4t_i\right) + \frac{1}{2} a^{peak2} \left(t_i^{min} - {}^4t_i\right)^2 \\ & + \frac{1}{6} J_i^{max} \left(t_i^{min} - {}^4t_i\right)^3 \end{aligned} \tag{B.12}$$

As described in Chap. 4.2.1, we calculated one of the unknowns, a_i^{peak1}, by transforming this system of equations to a root-finding problem. By applying the modified Anderson-Björck-King method (cf. Appendix A), we attained the value for a_i^{peak1}. All following steps are trivial, but for reasons of completeness, they are presented. The values for the other eleven unknown variables are derived successively, and the trajectory parameters of $\mathcal{M}_i$, that is, ${}^{l}\vec{m}_i(t)$ with $l \in \{1, \ldots, 4\}$ and ${}^{l}\vartheta_i$ with $l \in \{1, \ldots, 4\}$, are calculated.

$$ {}^{2}t_i = T_i + \frac{a_i^{peak1} - A_i}{J_i^{max}} \tag{B.13} $$

$$ {}^{3}t_i = {}^{2}t_i + \frac{a_i^{peak1}}{J_i^{max}} \tag{B.14} $$

$$ {}^{2}v_i = \left(\frac{1}{2}\,A_i - a_i^{peak1}\right)\left({}^{2}t_i - T_i\right) + 2V_i \tag{B.15} $$

$$ {}^{3}v_i = \frac{1}{2}\,a_i^{peak1}\,\left({}^{3}t_i - {}^{2}t_i\right) + {}^{2}v_i \tag{B.16} $$

$$ \begin{aligned} {}^{2}p_i = {} & V_i\,\left({}^{2}t_i - T_i\right) + \frac{1}{2}\,A_i\,\left({}^{2}t_i - T_i\right)^2 \\ & + \frac{1}{6}\,J_i^{max}\,\left({}^{2}t_i - T_i\right)^3 + P_i \end{aligned} \tag{B.17} $$

$$ \begin{aligned} {}^{3}p_i = {} & {}^{2}p_i + {}^{2}v_i\,\left({}^{3}t_i - {}^{2}t_i\right) + \frac{1}{2}\,a_i^{peak1}\,\left({}^{3}t_i - {}^{2}t_i\right)^2 \\ & - \frac{1}{6}\,J_i^{max}\,\left({}^{3}t_i - {}^{2}t_i\right)^3 \end{aligned} \tag{B.18} $$

$$ a_i^{peak2} = -\sqrt{J_i^{max}\left(V_i^{trgt} - {}^{3}v_i\right)} \tag{B.19} $$

$$ {}^{4}t_i = {}^{3}t_i - \frac{a_i^{peak2}}{J_i^{max}} \tag{B.20} $$

$$ t_i^{min} = {}^{4}t_i - \frac{a_i^{peak2}}{J_i^{max}} \tag{B.21} $$

$$ {}^{4}v_i = \frac{1}{2}\,a_i^{peak2}\,\left({}^{4}t_i - {}^{3}t_i\right) + {}^{3}v_i \tag{B.22} $$

$$ {}^{4}p_i = {}^{3}p_i + {}^{3}v_i\,\left({}^{4}t_i - {}^{3}t_i\right) - \frac{1}{6}\,J_i^{max}\,\left({}^{4}t_i - {}^{3}t_i\right)^3 \tag{B.23} $$

Now the system of equations is completely and uniquely solved, such that we obtain the correct and desired time-optimal trajectory. As a final step, we have to parameterize the elements of $\mathcal{M}_i$.

$$ {}^{1}\vartheta_i = \left[T_i, {}^{2}t_i\right] \qquad \text{(cf. eqn. (3.9), p. 34)} \tag{B.24} $$

$$ {}^{2}\vartheta_i = \left[{}^{2}t_i, {}^{3}t_i\right] \tag{B.25} $$

$$ {}^{3}\vartheta_i = \left[{}^{3}t_i, {}^{4}t_i\right] \tag{B.26} $$
$$ {}^{4}\vartheta_i = \left[{}^{4}t_i, t_i^{min}\right] \tag{B.27} $$

$$ {}^{1}\mathcal{V}_i = \left\{{}^{1}\vartheta_i\right\} \tag{B.28} $$
$$ {}^{2}\mathcal{V}_i = \left\{{}^{2}\vartheta_i\right\} \tag{B.29} $$
$$ {}^{3}\mathcal{V}_i = \left\{{}^{3}\vartheta_i\right\} \tag{B.30} $$
$$ {}^{4}\mathcal{V}_i = \left\{{}^{4}\vartheta_i\right\} \tag{B.31} $$

$$ {}^{1}j_i(t) = J_i^{max} \tag{B.32} $$
$$ {}^{2}j_i(t) = -J_i^{max} \tag{B.33} $$
$$ {}^{3}j_i(t) = -J_i^{max} \tag{B.34} $$
$$ {}^{4}j_i(t) = J_i^{max} \tag{B.35} $$

$$ {}^{1}a_i(t) = A_i + J_i^{max}(t - T_i) \tag{B.36} $$
$$ {}^{2}a_i(t) = a_i^{peak1} - J_i^{max}\left(t - {}^{2}t_i\right) \tag{B.37} $$
$$ {}^{3}a_i(t) = -J_i^{max}\left(t - {}^{3}t_i\right) \tag{B.38} $$
$$ {}^{4}a_i(t) = a_i^{peak2} + J_i^{max}\left(t - {}^{4}t_i\right) \tag{B.39} $$

$$ {}^{1}v_i(t) = V_i + A_i(t - T_i) + \frac{1}{2} J_i^{max}(t - T_i)^2 \tag{B.40} $$
$$ {}^{2}v_i(t) = {}^{1}v_i\left({}^{2}t_i\right) + a_i^{peak1}\left(t - {}^{2}t_i\right) - \frac{1}{2} J_i^{max}\left(t - {}^{2}t_i\right)^2 \tag{B.41} $$
$$ {}^{3}v_i(t) = {}^{2}v_i\left({}^{3}t_i\right) - \frac{1}{2} J_i^{max}\left(t - {}^{3}t_i\right)^2 \tag{B.42} $$
$$ {}^{4}v_i(t) = {}^{3}v_i\left({}^{4}t_i\right) + a_i^{peak2}\left(t - {}^{4}t_i\right) + \frac{1}{2} J_i^{max}\left(t - {}^{4}t_i\right)^2 \tag{B.43} $$

$$ {}^{1}p_i(t) = P_i + V_i(t - T_i) + \frac{1}{2} A_i(t - T_i)^2 + \frac{1}{6} J_i^{max}(t - T_i)^3 \tag{B.44} $$
$$ \begin{aligned} {}^{2}p_i(t) = {}^{1}p_i\left({}^{2}t_i\right) + {}^{1}v_i\left({}^{2}t_i\right)\left(t - {}^{2}t_i\right) + \frac{1}{2} a_i^{peak1}\left(t - {}^{2}t_i\right)^2 \\ - \frac{1}{6} J_i^{max}\left(t - {}^{2}t_i\right)^3 \end{aligned} \tag{B.45} $$
$$ {}^{3}p_i(t) = {}^{2}p_i\left({}^{3}t_i\right) + {}^{2}v_i\left({}^{3}t_i\right)\left(t - {}^{3}t_i\right) - \frac{1}{6} J_i^{max}\left(t - {}^{3}t_i\right)^3 \tag{B.46} $$

$$
{}^{4}p_i(t) = {}^{3}p_i\left({}^{4}t_i\right) + {}^{3}v_i\left({}^{4}t_i\right)\left(t - {}^{4}t_i\right) + \frac{1}{2}\, a_i^{peak2}\left(t - {}^{4}t_i\right)^2 + \frac{1}{6}\, J_i^{max}\left(t - {}^{4}t_i\right)^3 \tag{B.47}
$$

With

$$
{}^{l}\vec{m}_i(t) = \left({}^{l}p_i(t), {}^{l}v_i(t), {}^{l}a_i(t), {}^{l}j_i(t)\right) \quad \forall\, l \in \{1, \ldots, 4\} \tag{B.48}
$$

a one-dimensional Type IV, Variant A trajectory at time instant T_i $\mathcal{M}_i$ is completely described (cf. eqn. (3.10), p. 34):

$$
\mathcal{M}_i(t) = \left\{ \left({}^{1}\vec{m}_i(t), {}^{1}\mathcal{V}_i\right), \left({}^{2}\vec{m}_i(t), {}^{2}\mathcal{V}_i\right), \left({}^{3}\vec{m}_i(t), {}^{3}\mathcal{V}_i\right), \left({}^{4}\vec{m}_i(t), {}^{4}\mathcal{V}_i\right) \right\}. \tag{B.49}
$$

Appendix C
Details on the *PosTriZeroNegTri* Acceleration Profile (Step 2)

C.1 Position-Error Function

Written form of the position-error function for the Step 2 *PosTriZeroNegTri* acceleration profile:

$$
\begin{aligned}
&{}^{PosTriZeroNegTri}p_i^{err2}\left(a_i^{peak1}\right) = \frac{1}{48\ \left({}_kJ_i^{max}\right)^3}\Bigg(-8\,\left({}_kA_i\right)^3\left({}_kJ_i^{max}\right)\\
&+48\,{}_kA_i\left({}_ka_i^{peak1}\right)^2\left({}_kJ_i^{max}\right)+30\,\left({}_kA_i\right)^2\Bigg(-80\left(t_i^{sync}\right)\left({}_kJ_i^{max}\right)^2+\sqrt{18}\left({}_kJ_i^{max}\right)\\
&\Bigg(\sqrt{\Bigg(-\left({}_kA_i\right)^2+2\Bigg(\left({}_ka_i^{peak1}\right)^2+\left({}_kJ_i^{max}\right)\left({}_kV_i-\left({}_kV_i^{trgt}\right)\right)\Bigg)\Bigg)}\\
&+\sqrt{-2\left({}_kA_i\right)^2+4\Bigg(\left({}_ka_i^{peak1}\right)^2+\left({}_kJ_i^{max}\right)\left({}_kV_i-\left({}_kV_i^{trgt}\right)\right)\Bigg)}\Bigg)\Bigg)-6\Bigg(8\left({}_ka_i^{peak1}\right)^3\\
&\left({}_kJ_i^{max}\right)+\left({}_kJ_i^{max}\right)\Bigg(-8\left({}_kJ_i^{max}\right)^2\left({}_kP_i-{}_kP_i^{trgt}+\left(t_i^{sync}\right){}_kV_i\right)+\left({}_kJ_i^{max}\right)\\
&\left({}_kV_i-\left({}_kV_i^{trgt}\right)\right)\sqrt{-2\left({}_kA_i\right)^2+4\left({}_ka_i^{peak1}\right)^2+4\left({}_kJ_i^{max}\right)\left({}_kV_i-\left({}_kV_i^{trgt}\right)\right)}+\sqrt{18}\\
&\left({}_kV_i-\left({}_kV_i^{trgt}\right)\right)\left({}_kJ_i^{max}\right)\sqrt{\Bigg(-\left({}_kA_i\right)^2+2\left({}_ka_i^{peak1}\right)^2+2\left({}_kJ_i^{max}\right)\left({}_kV_i-\left({}_kV_i^{trgt}\right)\right)\Bigg)}\Bigg)\\
&+\left({}_ka_i^{peak1}\right)^2\Bigg(-8\left(t_i^{sync}\right)\left({}_kJ_i^{max}\right)^2+\sqrt{18}\left({}_kJ_i^{max}\right)\\
&\Bigg(\sqrt{\Bigg(-\left({}_kA_i\right)^2+2\Bigg(\left({}_ka_i^{peak1}\right)^2+\left({}_kJ_i^{max}\right)\left({}_kV_i-\left({}_kV_i^{trgt}\right)\right)\Bigg)\Bigg)}\\
&+\sqrt{-2\left({}_kA_i\right)^2+4\Bigg(\left({}_ka_i^{peak1}\right)^2+\left({}_kJ_i^{max}\right)\left({}_kV_i-\left({}_kV_i^{trgt}\right)\right)\Bigg)}\Bigg)\Bigg)\Bigg)\Bigg)\ .
\end{aligned}
$$

C.2 Setting up the Parameters of $\mathcal{M}_i$

In order to achieve a completely described derivation of the Type IV on-line trajectory generation algorithm, the calculations of the unknown variables of eqns. (5.29) – (5.42) (Chap. 5.3.1, p. 88) are presented here. Afterwards, all parameters of the final trajectory $\mathcal{M}_i$ at time instant T_i are calculated for one DOF k.

Analogous to App. B.3 we again repeat the respective system of equations represented by eqns. (5.29) – (5.42).

$$ {}_k^2t_i - T_i = \frac{\left({}_ka^{peak1} - {}_kA_i\right)}{{}_kJ_i^{max}} \tag{C.1} $$

$$ {}_k^3t_i - {}_k^2t_i = \frac{{}_ka^{peak1}}{{}_kJ_i^{max}} \tag{C.2} $$

$$ {}_k^5t_i - {}_k^4t_i = -\frac{{}_ka^{peak2}}{{}_kJ_i^{max}} \tag{C.3} $$

$$ t_i^{sync} - {}_k^5t_i = -\frac{{}_ka^{peak2}}{{}_kJ_i^{max}} \tag{C.4} $$

$$ {}_k^2v_i - V_i = \frac{1}{2}\left({}_k^2t_i - T_i\right)\left({}_kA_i + {}_ka^{peak1}\right) \tag{C.5} $$

$$ {}_k^3v_i - {}_k^2v_i = \frac{1}{2}\left({}_k^3t_i - {}_k^2t_i\right)\ {}_ka^{peak1} \tag{C.6} $$

$$ {}_k^4v_i - {}_k^3v_i = 0 \tag{C.7} $$

$$ {}_k^5v_i - {}_k^4v_i = \frac{1}{2}\left({}_k^5t_i - {}_k^4t_i\right)\ {}_ka^{peak2} \tag{C.8} $$

$$ {}_kV_i^{trgt} - {}_k^5v_i = \frac{1}{2}\left(t_i^{sync} - {}_k^5t_i\right)\ {}_ka^{peak2} \tag{C.9} $$

$$ \begin{aligned} {}_k^2p_i - {}_kP_i = {}&{}_kV_i\ \left({}_k^2t_i - T_i\right) + \frac{1}{2}\ {}_kA_i\ \left({}_k^2t_i - T_i\right)^2 \\ &+ \frac{1}{6}\ {}_kJ_i^{max}\ \left({}_k^2t_i - T_i\right)^3 \end{aligned} \tag{C.10} $$

$$ \begin{aligned} {}_k^3p_i - {}_k^2p_i = {}&{}_k^2v_i\ \left({}_k^3t_i - {}_k^2t_i\right) + \frac{1}{2}\ {}_ka_i^{peak1}\ \left({}_k^3t_i - {}_k^2t_i\right)^2 \\ &- \frac{1}{6}\ {}_kJ_i^{max}\ \left({}_k^3t_i - {}_k^2t_i\right)^3 \end{aligned} \tag{C.11} $$

$$ {}_k^4p_i - {}_k^3p_i = {}_k^3v_i\ \left({}_k^4t_i - {}_k^3t_i\right) \tag{C.12} $$

$$ {}_k^5p_i - {}_k^4p_i = {}_k^4v_i\ \left({}_k^5t_i - {}_k^4t_i\right) - \frac{1}{6}\ {}_kJ_i^{max}\ \left({}_k^5t_i - {}_k^4t_i\right)^3 \tag{C.13} $$

$$ \begin{aligned} {}_kP_i^{trgt} - {}_k^5p_i = {}&{}_k^5v_i\ \left(t_i^{sync} - {}_k^5t_i\right) + \frac{1}{2}\ {}_ka_i^{peak2}\ \left(t_i^{sync} - {}_k^5t_i\right)^2 \\ &+ \frac{1}{6}\ {}_kJ_i^{max}\ \left(t_i^{sync} - {}_k^5t_i\right)^3 \end{aligned} \tag{C.14} $$

These 14 equations contain 14 unknown variables: ${}_k^2t_i$, ${}_k^3t_i$, ${}_k^4t_i$, ${}_k^5t_i$, ${}_k^2v_i$, ${}_k^3v_i$, ${}_k^4v_i$, ${}_k^5v_i$, ${}_k^2p_i$, ${}_k^3p_i$, ${}_k^4p_i$, ${}_k^5p_i$, ${}_ka_i^{peak1}$, and ${}_ka_i^{peak2}$. The calculation of the first unknown, ${}_ka_i^{peak1}$, was already described in Chap. 5.3.1 (p. 89). As in App. B.3, the following calculation of the other 13 unknown variables can be successively derived in a straightforward way:

$$ {}_k^2t_i = T_i + \frac{{}_ka_i^{peak1} - {}_kA_i}{{}_kJ_i^{max}} \tag{C.15} $$

$$ {}_k^3t_i = {}_k^2t_i + \frac{{}_ka_i^{peak1}}{{}_kJ_i^{max}} \tag{C.16} $$

$$ {}_k^2v_i = \left(\frac{1}{2}\,{}_kA_i - {}_ka_i^{peak1}\right)\left({}_k^2t_i - T_i\right) + 2\,{}_kV_i \tag{C.17} $$

$$ {}_k^3v_i = \frac{1}{2}\,{}_ka_i^{peak1}\left({}_k^3t_i - {}_k^2t_i\right) + {}_k^2v_i \tag{C.18} $$

$$ \begin{aligned} {}_k^2p_i = {}& {}_kV_i\left({}_k^2t_i - T_i\right) + \frac{1}{2}\,{}_kA_i\left({}_k^2t_i - T_i\right)^2 \\ & + \frac{1}{6}\,{}_kJ_i^{max}\left({}_k^2t_i - T_i\right)^3 + {}_kP_i \end{aligned} \tag{C.19} $$

$$ \begin{aligned} {}_k^3p_i = {}& {}_k^2p_i + {}_k^2v_i\left({}_k^3t_i - {}_k^2t_i\right) + \frac{1}{2}\,{}_ka_i^{peak1}\left({}_k^3t_i - {}_k^2t_i\right)^2 \\ & - \frac{1}{6}\,{}_kJ_i^{max}\left({}_k^3t_i - {}_k^2t_i\right)^3 \end{aligned} \tag{C.20} $$

$$ {}_ka_i^{peak2} = -\sqrt{{}_kJ_i^{max}\left({}_kV_i^{trgt} - {}_k^3v_i\right)} \tag{C.21} $$

$$ {}_k^5t_i = t_i^{sync} + \frac{{}_ka_i^{peak2}}{{}_kJ_i^{max}} \tag{C.22} $$

$$ {}_k^5v_i = {}_kV_i^{trgt} - \frac{1}{2}\,{}_ka_i^{peak2}\left(t_i^{sync} - {}_k^5t_i\right) \tag{C.23} $$

$$ \begin{aligned} {}_k^5p_i = {}& {}_kP_i^{trgt} - {}_k^5v_i\left(t_i^{sync} - {}_k^5t_i\right) - \frac{1}{2}\,{}_ka_i^{peak2}\left(t_i^{sync} - {}_k^5t_i\right)^2 \\ & - \frac{1}{6}\,{}_kJ_i^{max}\left(t_i^{sync} - {}_k^5t_i\right)^3 \end{aligned} \tag{C.24} $$

$$ {}_k^4t_i = {}_k^5t_i + \frac{{}_ka_i^{peak2}}{{}_kJ_i^{max}} \tag{C.25} $$

$$ {}_k^4v_i = {}_k^3v_i \tag{C.26} $$

$$ {}_k^4p_i = {}_k^5p_i - {}_k^4v_i\left({}_k^5t_i - {}_k^4t_i\right) + \frac{1}{6}\,{}_kJ_i^{max}\left({}_k^5t_i - {}_k^4t_i\right)^3 . \tag{C.27} $$

Therewith, we know the complete and unique solution of eqns. (C.1) – (C.14), such that we can finally set the trajectory parameters of $\mathcal{M}_i$, which describe motion of DOF k.

$$ {}_k^1\vartheta_i = \left[T_i,\, {}_k^2t_i\right] \tag{C.28}$$
$$ {}_k^2\vartheta_i = \left[{}_k^2t_i,\, {}_k^3t_i\right] \tag{C.29}$$
$$ {}_k^3\vartheta_i = \left[{}_k^3t_i,\, {}_k^4t_i\right] \tag{C.30}$$
$$ {}_k^4\vartheta_i = \left[{}_k^4t_i,\, {}_k^5t_i\right] \tag{C.31}$$
$$ {}_k^5\vartheta_i = \left[{}_k^5t_i,\, t_i^{sync}\right] \tag{C.32}$$

$$ {}_k^1j_i(t) = {}_kJ_i^{max} \tag{C.33}$$
$$ {}_k^2j_i(t) = -{}_kJ_i^{max} \tag{C.34}$$
$$ {}_k^3j_i(t) = 0 \tag{C.35}$$
$$ {}_k^4j_i(t) = -{}_kJ_i^{max} \tag{C.36}$$
$$ {}_k^5j_i(t) = {}_kJ_i^{max} \tag{C.37}$$

$$ {}_k^1a_i(t) = {}_kA_i \;+\; {}_kJ_i^{max}\left(t \;-\; T_i\right) \tag{C.38}$$
$$ {}_k^2a_i(t) = {}_ka_i^{peak1} \;-\; {}_kJ_i^{max}\left(t \;-\; {}_k^2t_i\right) \tag{C.39}$$
$$ {}_k^3a_i(t) = 0 \tag{C.40}$$
$$ {}_k^4a_i(t) = -{}_kJ_i^{max}\left(t \;-\; {}_k^4t_i\right) \tag{C.41}$$
$$ {}_k^5a_i(t) = {}_ka_i^{peak2} \;+\; {}_kJ_i^{max}\left(t \;-\; {}_k^5t_i\right) \tag{C.42}$$

$$ {}_k^1v_i(t) = {}_kV_i \;+{}_kA_i\left(t \;-\; T_i\right) \;+\; \frac{1}{2}\;{}_kJ_i^{max}\left(t \;-\; T_i\right)^2 \tag{C.43}$$
$$ {}_k^2v_i(t) = {}_k^1v_i\left({}_k^2t_i\right) \;+\; {}_ka_i^{peak1}\left(t \;-\; {}_k^2t_i\right) \;-\; \frac{1}{2}\;{}_kJ_i^{max}\left(t \;-\; {}_k^2t_i\right)^2 \tag{C.44}$$
$$ {}_k^3v_i(t) = {}_k^3v_i \tag{C.45}$$
$$ {}_k^4v_i(t) = {}_k^3v_i\left({}_k^4t_i\right) \;-\; \frac{1}{2}\;{}_kJ_i^{max}\left(t \;-\; {}_k^4t_i\right)^2 \tag{C.46}$$
$$ {}_k^5v_i(t) = {}_k^4v_i\left({}_k^5t_i\right) \;+\; {}_ka_i^{peak2}\left(t \;-\; {}_k^5t_i\right) \;+\; \frac{1}{2}\;{}_kJ_i^{max}\left(t \;-\; {}_k^5t_i\right)^2 \tag{C.47}$$

$$ \begin{aligned} {}_k^1p_i(t) = {}&{}_kP_i \;+\; {}_kV_i\left(t \;-\; T_i\right) \;+\; \frac{1}{2}\;{}_kA_i\left(t \;-\; T_i\right)^2 \\ &+\; \frac{1}{6}\;{}_kJ_i^{max}\left(t \;-\; T_i\right)^3 \end{aligned} \tag{C.48}$$
$$ {}_k^2p_i(t) = {}_k^1p_i\left({}_k^2t_i\right) \;+\; {}_k^1v_i\left({}_k^2t_i\right)\left(t \;-\; {}_k^2t_i\right) \;+\; \frac{1}{2}\;{}_ka_i^{peak1}\left(t \;-\; {}_k^2t_i\right)^2$$

$$- \frac{1}{6}\,{}_kJ_i^{max}\left(t - {}_k^2t_i\right)^3 \tag{C.49}$$

$$ {}_k^3p_i(t) = {}_k^2p_i\left({}_k^3t_i\right) + {}_k^3v_i\left({}_k^3t_i\right)\left(t - {}_k^3t_i\right) \tag{C.50}$$

$$ {}_k^4p_i(t) = {}_k^3p_i\left({}_k^4t_i\right) + {}_k^3v_i\left({}_k^4t_i\right)\left(t - {}_k^4t_i\right) - \frac{1}{6}\,{}_kJ_i^{max}\left(t - {}_k^4t_i\right)^3 \tag{C.51}$$

$$ {}_k^5p_i(t) = {}_k^4p_i\left({}_k^5t_i\right) + {}_k^4v_i\left({}_k^5t_i\right)\left(t - {}_k^5t_i\right) + \frac{1}{2}\,{}_ka_i^{peak2}\left(t - {}_k^5t_i\right)^2 + \frac{1}{6}\,{}_kJ_i^{max}\left(t - {}_k^5t_i\right)^3 \tag{C.52}$$

With the results of eqns. (C.28) – (C.52), we can finally set up all trajectory parameters for one single DOF k at time instant T_i

$$ {}^l\vec{m}_i(t) = \left({}^lp_i(t), {}^lv_i(t), {}^la_i(t), {}^lj_i(t)\right) \quad \forall\, l \in \{1, \ldots, 5\} \tag{C.53}$$

$$ {}_k^l\vartheta_i \in {}^l\mathcal{V}_i \quad \forall\, l \in \{1, \ldots, 5\}\ . \tag{C.54}$$

Equations (C.53) and (C.54) represent the DOF k in $\mathcal{M}_i$ (cf. eqns. (3.9) and (3.10), p. 34).

Appendix D
Type IV On-Line Trajectory Generation in Very Simple Terms

The purpose of this appendix chapter is to describe the Type IV on-line trajectory generation algorithm in a less scientific but more metaphoric and descriptive way by means of a very simple example. The chapter does not contain new information, but only illustrates a part of this book in a plain and comprehensive way.

D.1 The Rocket Car Example

In the figurative sense, we can consider a rocket car as depicted in Fig. D.1 for the representation of a single DOF of a system to be controlled by the on-line trajectory generator. We assume an idealized car, *massless* and *without any friction*. We only can control the car by turning a lever as shown in Fig. D.1. If the lever is at its rightmost position, the right rocket runs at full power, which corresponds to an acceleration with $-A_i^{max}$, the maximum available acceleration value at time T_i. If the lever is positioned exactly centered, both rockets are turned off, and the car is not accelerated in any direction. Analogously, the car will accelerate with $A_i = A_i^{max}$ if the lever is in its leftmost position. A_i^{max} is the power of our rocket motor. At first sight, this sounds easy, but there is an additional restriction: The car possesses a *maximum lever-turning velocity* J_i^{max}, that is, we are not allowed to turn the

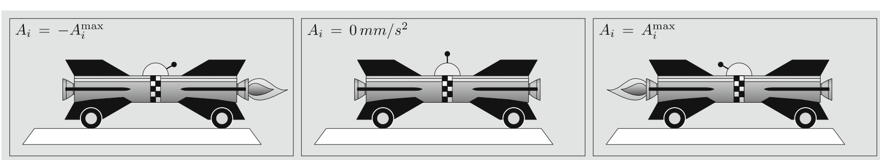

Fig. D.1 Illustration of the rocket car in three different acceleration states: $A_i = -A_i^{max}$, $A_i = 0mm/s^2$, and $A_i = A_i^{max}$.

lever jerkily. This leads to the consequence that the resulting acceleration progression is jump-free and the jerk of the car is limited.

D.2 Type IV OTG for One-DOF Systems

This appendix section takes up the approach for Type IV OTG from Chap. 4 (p. 45). Let us first transfer the problem formulation for the one-dimensional case to the rocket car example. Imagine that we work with time slices of T^{cycle} width.[1] Then, the time difference from one slice T_i to the next one T_{i+1} is T^{cycle}. At T_i, the algorithm gets the input values $\vec{W}_i$ as illustrated in Fig. D.2. To explain this more simply, it means that the car is at position P_i, drives with a velocity V_i, and accelerates with A_i. Summarized, this is the current state of motion $\vec{M}_i$. It is our task to reach the target position P_i^{trgt} in the shortest possible time. Furthermore, we want drive through P_i^{trgt} with a certain target velocity V_i^{trgt}. These two values, P_i^{trgt} and V_i^{trgt}, constitute the target state of motion $\vec{M}_i^{trgt}$. The target acceleration A_i^{trgt} has to be zero. It is our aim to transfer our car's current state of motion $\vec{M}_i$ to its target state of motion $\vec{M}_i^{trgt}$ in the shortest possible time t_i^{min}. Here, we have to take care for some motion constraints: Our car features a maximum velocity V_i^{max}, the power of its rocket motor is limited to A_i^{max}, and the maximum lever-turning velocity for controlling the rocket motor is J_i^{max}. These three boundary values are summarized in the vector $\vec{B}_i$.

Hence, the question here is: How can we calculate a trajectory that lets the car reach $\vec{M}_i^{trgt}$ in the shortest possible time? Because we want to be able to react to any unforeseen events instantaneously, for example, a thinking scientist could cross our way, we are only interested in the result for the time slice T_i. That means, even if we have to calculate the whole trajectory for reaching $\vec{M}_i^{trgt}$, we are only interested in the state of motion at the time slice T_{i+1}, that is, $\vec{M}_{i+1}$. As the last value, we have to consider S_i. S_i may be compared to a power on/off button for the OTG algorithm: If S_i is *one*, we have to calculate $\vec{M}_{i+1}$, and if S_i is *zero*, nobody is interested in our service, and we do not have to do anything. At the next time slice T_{i+1}, the algorithm starts over again and calculates the state of motion $\vec{M}_{i+2}$ without using any knowledge from the last time slice, because the input values could have unexpectedly changed.

In Chap. 3.2.2 (p. 39), we also distinguish between OTG Type IV, Variant A and OTG Type IV, Variant B. If we transfer this distinction to our rocket car, we can say that the Variant A algorithm works with constant boundary values $\vec{B}_i$ for all time slices. That means our maximum velocity, the power of the rocket motor, and the maximum lever-turning velocity do not change over time. The B-Variant is furthermore able to cope with changing elements of $\vec{B}_i$, that is, depending on the time slice, the power of the rocket motor

[1] A typical value for T^{cycle} is one millisecond.

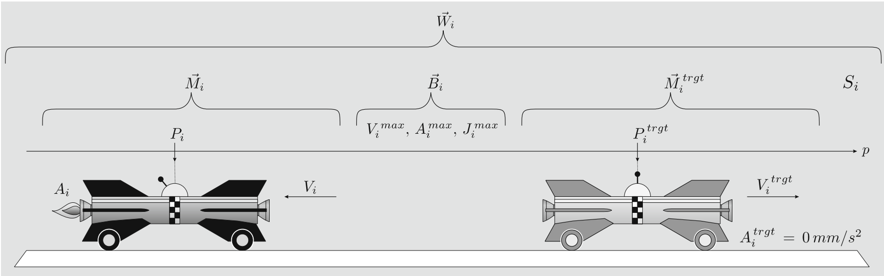

Fig. D.2 Illustration by means of the rocket car example: input values $\vec{W}_i$ at time T_i of the Type IV on-line trajectory generation algorithm for the one-dimensional case.

may change, the maximum velocity may change, or even the maximum lever-turning velocity may change.

In Chap. 4.2 (p. 49) the algorithm that solves this problem for Variant A and Variant B, is discussed with all details and nuances.

D.3 Type IV OTG for Multi-DOF Systems

We now extend the rocket car example of the previous section in order to apply the Type IV OTG algorithm to systems with multiple DOFs, for example, robots with multiple joints. We continue using the same non-scientific and plain way of presentation of the previous section.

Actually, we have to solve almost the same problem as in the one-dimensional case of Fig. D.2, but instead of only one rocket car, we now consider K independently driving rocket cars, as depicted in Fig. D.3. Each car is identified by the index k, and each car is assumed to be in a motion state ${}_k\vec{M}_i$, that is, the car with the index k is located at position ${}_kP_i$, at which it drives with a velocity ${}_kV_i$, and exerts a certain acceleration ${}_kA_i$. Analogous to the one-dimensional case, each car is assigned with a target state of motion ${}_k\vec{M}_i^{trgt}$ and some motion constraints ${}_k\vec{B}_i$. The aim of the Type IV on-line trajectory generation algorithm is to guide each car from its initial state of motion to its target state of motion in the shortest possible time — this is clear. But the additional challenge is to specify an algorithm that lets all K cars reach their target states of motion at the very same time: at the minimum possible synchronization time t_i^{sync}. Hence, the question to be answered here is: How can we calculate K trajectories, such that all K cars synchronously reach their state of motion in the shortest possible time?

As described in the previous section, each car can be turned on or off by the vector

$$\vec{S}_i = \left({}_1S_i, \ldots, {}_kS_i, \ldots, {}_KS_i\right) \ , \tag{D.1}$$

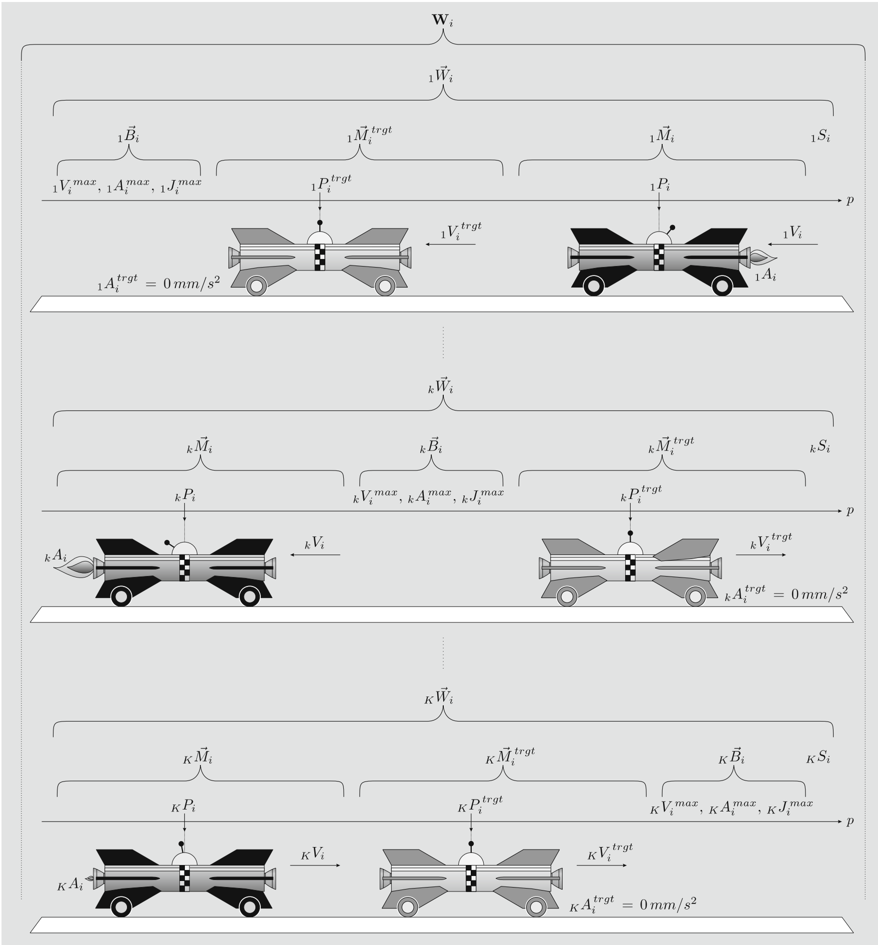

Fig. D.3 Illustration by means of the rocket car example: input values $\mathbf{W}_i$ of the Type IV on-line trajectory generation algorithm for a system with K independently acting DOFs at time T_i.

whose elements contain either a *one* or a *zero*. Hence, a rocket car is only taken into account if the corresponding element of the vector $\vec{S}_i$ equals *one*. If the respective value ${}_kS_i$ for the car with the index k is *zero*, the car will not be guided by the algorithm.

For a more compact embodiment of all these numbers, the matrix $\mathbf{W}_i$ is introduced at the top of Fig. D.3 and contains all necessary input variables of the OTG Type IV algorithm.

This algorithm is executed once per time slice, which again is represented by T_i; at each time slice three basic steps are executed:

1. Based on the input values $\mathbf{W}_i$, we calculate the minimum possible synchronization time t_i^{sync}. This time cannot be lower than the ride time of the rocket car with the greatest ride time.
2. We calculate a complete trajectory for each selected car, and we guarantee, that all selected cars will reach their target state of motion exactly at the time t_i^{sync}.
3. The output of the algorithm is calculated based on the result of Step 2 and only contains the state of motion for the current time slice.

Thus, we are able to react to unforeseen events (e.g., sudden slowdowns of cars in front of us) *immediately* after they are detected. The reaction time is not greater than T^{cycle}.

At the next time slice, T_{i+1}, we execute the same memoryless algorithm again. If nothing has happened, the previously calculated values ${}_1M_{i+1}, \ldots, {}_kM_{i+1}, \ldots, {}_KM_{i+1}$ are used as new input values for the time slice at T_{i+1}.

The difference between the A- and B-Variants is exactly the same as in the one-dimensional case, that is, Variant B is an extension of Variant A, which additionally can cope with varying values of ${}_1B_i, \ldots, {}_kB_i, \ldots, {}_KB_i$.

The algorithm, which can control the cars this way, is explained in detail in Chap. 5.3 (p. 80).

Remark D.1. *If written in the style of Chap. 5.3, the current motion states of all rocket cars can be simply summarized by*

$$\mathbf{M}_i = \left({}_1\vec{M}_i, \ldots, {}_k\vec{M}_i, \ldots, {}_K\vec{M}_i\right)^T \quad , \tag{D.2}$$

and the same can easily be applied to the target states of motion and the motion constraints:

$$\mathbf{M}_i^{trgt} = \left({}_1\vec{M}_i^{trgt}, \ldots, {}_k\vec{M}_i^{trgt}, \ldots, {}_K\vec{M}_i^{trgt}\right)^T \tag{D.3}$$

$$\mathbf{B}_i = \left({}_1\vec{B}_i, \ldots, {}_k\vec{B}_i, \ldots, {}_K\vec{B}_i\right)^T \quad . \tag{D.4}$$

Finally, we can express all input values $\mathbf{W}_i$ *by*

$$\begin{aligned}\mathbf{W}_i &= \left({}_1\vec{W}_i, \ldots, {}_k\vec{W}_i, \ldots, {}_K\vec{W}_i\right)^T \\ &= \left(\mathbf{M}_i, \mathbf{M}_i^{trgt}, \mathbf{B}_i, \vec{S}_i\right) \quad .\end{aligned} \tag{D.5}$$

Abbreviations and Symbols

Abbreviations

BF : Robot base frame
CCD : Charge Coupled Device
CNC : Computer numerical control
DOF : Degree of freedom
EF : External frame
HF : Robot hand frame
HMI : Human machine interface
MP : Manipulation Primitive
NURBS : Non-uniform, rational B-splines
OTG : On-line trajectory generation
PRM : Probabilistic road map
RRT : Rapidly exploring random trees
RAMP : Real-time adaptive motion planning
TF : Task Frame
VGA : Video graphics adapter

Symbols

Introduction (Chaps. 1 – 2)

$\vec{f}(t)$	: Forces and/or torques in joint space	(p. 2)
$\vec{p}(t)$	: Position in task space	(p. 3)
$\dot{\vec{p}}(t)$	: Velocity in task space	(p. 3)
$\ddot{\vec{p}}(t)$	: Acceleration in task space	(p. 3)
$\vec{p}_d(t)$	: Position set-point in task space	(p. 3)
$\dot{\vec{p}}_d(t)$	: Velocity set-point in task space	(p. 3)
$\ddot{\vec{p}}_d(t)$	: Acceleration set-point in task space	(p. 3)
$\vec{q}(t)$	: Position in joint space	(p. 2)

$\vec{\dot{q}}(t)$	: Velocity in joint space	(p. 2)
$\vec{\ddot{q}}(t)$	: Acceleration in joint space	(p. 2)
$\vec{q}_d(t)$	: Position set-point in joint space	(p. 2)
$\vec{\dot{q}}_d(t)$	: Velocity set-point in joint space	(p. 2)
$\vec{\ddot{q}}_d(t)$	: Acceleration set-point in joint space	(p. 2)
$\vec{s}(t)$	: Generic sensor signal in task space	(p. 3)
$\vec{s}_d(t)$	: Command variable in task space	(p. 3)

On-line trajectory generation (Chaps. 3 – 6 and 8 – 10)

$a_0, \ldots, a_4$	: Polynomial coefficients	(p. 34)
${}^l\vec{a}_i(t)$	: Vector of acceleration polynomials at T_i and segment l	(p. 34)
$\vec{A}_i$	: Acceleration vector at T_i	(p. 33)
${}_kA_i$	: Acceleration magnitude for DOF k vector at T_i	(p. 33)
$\vec{A}_i^{max}$	: Vector of maximum accelerations at T_i	(p. 34)
α	: Type-dependent integer value for the classification of OTG	(p. 38)
$\vec{B}_i$	: Motion constraints for one single DOF at T_i	(p. 45)
$\mathbf{B}_i$	: Matrix of boundary conditions for motion properties atT_i	(p. 34)
β	: Type-dependent integer value for the classification of OTG	(p. 38)
$\mathbb{B}$	: Set of binary numbers	(p. 37)
γ	: Vector with $\alpha - \beta - 2$ elements to check for colinearity	(p. 101)
${}_kD_i$	: Magnitude of the derivative of jerk for DOF k vector at T_i	(p. 33)
$\vec{D}_i$	: Vector of the derivative of jerk at T_i	(p. 33)
$\vec{D}_i^{max}$	: Vector of maximum derivatives of jerk at T_i	(p. 34)
δ	: Vector with β elements to check for colinearity	(p. 103)
${}^r\mathcal{D}_{Step1}$	: Domain for the system of equations of the motion profile ${}^r\boldsymbol{\Psi}^{Step1}$	(p. 48)
h	: Index of a concrete intermediate motion state	(p. 161)
H	: Number of intermediate motion states	(p. 161)
$\mathcal{H}$	: Set of holes in the $(\alpha+1)$-dimensional space	(p. 76)
i	: Index for one time instant T_i	(p. 33)
${}_k\mathcal{I}_i$	: Set of time instants for a DOF k at T_i	(p. 73)
${}^l\vec{j}_i(t)$	: Vector of jerk polynomials at T_i and segment l	(p. 34)
$\vec{J}_i$	: Jerk vector at T_i	(p. 33)
$\vec{J}_i^{max}$	: Vector of maximum jerks at T_i	(p. 34)
${}_kJ_i$	: Jerk magnitude for DOF k vector at T_i	(p. 33)
k	: One single DOFs with $k \in \{1, \ldots, K\}$	(p. 33)
K	: Number of DOFs	(p. 33)
κ	: One single DOFs with the index $\kappa \in \{1, \ldots, K\}$	(p. 99)
l	: One single trajectory segment with $l \in \{1, \ldots, L\}$	(p. 34)

L	: Maximum number of trajectory segments	(p. 34)
λ	: Number of control cycles for parameter adaptation	(p. 165)
Λ	: Number of intermediate trajectory segments	(p. 46)
${}^{l}_{k}\vec{m}_i(t)$	: Vector of motion polynomials of segment l and DOF k at time T_i	(p. 34)
${}^{l}\mathbf{m}_i(t)$	: Matrix of motion polynomials of segment l at time T_i	(p. 34)
$\vec{M}_i$	: State of motion for one single DOF at T_i	(p. 45)
$\mathbf{M}_i$	: Motion state matrix at T_i	(p. 33)
$\mathbf{M}_i^{trgt}$	: Matrix containing the target state of motion a T_i	(p. 34)
$\mathcal{M}_i(t)$	: Parameterized trajectory at time T_i	(p. 34)
$\mathbb{N}$	: Set of natural numbers	(p. 49)
ν	: Number of cycles in-between two (visual servo control) set-points	(p. 159)
${}^{l}\vec{p}_i(t)$	: Vector of position polynomials at T_i and segment l	(p. 34)
${}_{k}P_i$	: Position magnitude for DOF k at T_i	(p. 33)
$\vec{P}_i$	: Position vector at T_i	(p. 33)
${}^{r}\Psi^{Step1}$	: Motion profile r for Step 1 (element of $\mathcal{P}_{Step1}$)	(p. 47)
$\mathcal{P}_{Step1}$	: Set of motion profiles for Step 1	(p. 47)
r	: Index for Step 1 motion profiles	(p. 47)
R	: Total number of elements of $\mathcal{P}_{Step1}$	(p. 47)
$\vec{\rho}_i$	: Ratio vector for homothety at T_i	(p. 99)
$\mathbb{R}$	: Set of real numbers	(p. 39)
s	: Index for Step 2 motion profiles	(p. 76)
S	: Total number of elements of $\mathcal{P}_{Step2}$	(p. 76)
$\vec{S}_i$	: Selection vector at T_i	(p. 37)
$\mathcal{S}$	: Intersection of all Step 2 input domains	(p. 78)
Δt	: Value for polynomial time-shifting	(p. 34)
${}_{k}t_i^{min}$	: Minimum possible execution time for DOF k calculated at T_i	(p. 46)
t_i^{sync}	: Synchronization time calculated at T_i	(p. 35)
T^{cycle}	: Control cycle time	(p. 33)
$\mathcal{T}$	: Set of time instants	(p. 33)
T_0, T_i, T_N	: Discrete time instants of $\mathcal{T}$	(p. 33)
${}_{k}\tilde{v}_i$	: Velocity achieved by a peak-peak accel. profile for DOF k at T_i	(p. 91)
${}^{l}\vec{v}_i(t)$	: Vector of velocity polynomials at T_i and segment l	(p. 34)
${}_{k}V_i$	: Velocity magnitude for DOF k vector at T_i	(p. 33)
$\vec{V}_i$	: Velocity vector at T_i	(p. 33)
$\vec{V}_i^{max}$	: Vector of maximum velocities at T_i	(p. 34)
${}^{l}_{k}\vartheta_i$	: Time interval for segment l and DOF k at time T_i	(p. 34)
${}^{l}\mathcal{V}_i$	: Set of time intervals for segment l at time T_i	(p. 34)
$\vec{W}_i$	: OTG input values for one single DOF at T_i	(p. 45)
$\mathbf{W}_i$	: All input parameters of the OTG algorithm	(p. 37)
${}^{z}_{k}\zeta_i$	: z-th inoperative time interval for DOF k at T_i	(p. 71)

${}_k\mathcal{Z}_i$: Set of inoperative time intervals for DOF k at T_i (p. 70)
$\mathbb{Z}$: Set of integer numbers (p. 39)

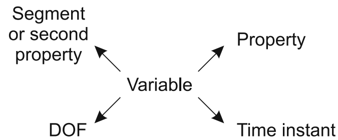

Fig. S.1 Convention for sub- and superscripts of all variables except sets and profiles.

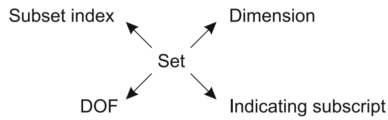

Fig. S.2 Convention for sub- and superscripts of sets.

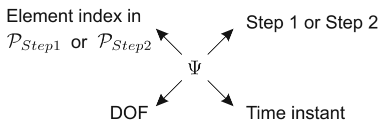

Fig. S.3 Convention for sub- and superscripts of profiles.

Hybrid Switched-System Control (Chap. 7)

ANC_i : Anchor frame of the Task Frame at T_i (p. 110)
BF : Robot base frame (updated by the system every control cycle) (p. 110)
$\mathbb{B}$: Set of binary numbers (p. 119)
c : Index for one control submodule $c \in \mathcal{C}$ (p. 110)
$\mathcal{C}$: Set of all m control submodules in the hybrid switched-system (p. 111)
${}^l_kD^c_i$: One single set-point for controller c, level l, and DOF k at T_i (p. 110)
$\mathcal{D}_i$: Set-point set of a hybrid move command $\mathcal{HM}_i$ at T_i (p. 110)
EF : External frame (updated by the system every control cycle) (p. 110)
$\mathbf{E}_i$: Flag assignment matrix at T_i (p. 122)
$\vec{f}^c_i$: Availability flag vector for controller c at T_i (p. 120)
FFC_i : Frame for feedforward control of the Task Frame at T_i (p. 110)
$\mathbf{F}^c_i$: Availability matrix for controller c at T_i (p. 120)

$\mathbf{G}_i^r$: Control variable assignment matrix with $r \in \{pos, vel, acc\}$ at T_i (p. 121)
$\mathbf{H}_i$: Adaptive selection matrix at time T_i $\mathcal{MP}_i$ at T_i (p. 121)
HF : Hand frame (updated by the system every control cycle) (p. 110)
$\mathcal{HM}_i$: Parameter set of a hybrid move command of $\mathcal{MP}_i$ at T_i (p. 109)
i : Index for one time instant T_i (p. 109)
I : Identity matrix (p. 117)
k : Index for one DOF $k \in \mathcal{K}$ (p. 110)
$\mathcal{K}$: Set of all DOFs $\{x, y, z, x, y, z\}$ (p. 111)
l : Index for one level $l \in \mathcal{L}$ (p. 110)
λ_i : Stop condition of a manipulation primitive $\mathcal{MP}_i$ at T_i (p. 109)
$\mathcal{L}$: Set of all control m levels (p. 111)
m : Number of control submodules in the hybrid switched-system (p. 111)
${}^A\mathbf{M}_i^B$: Motion state of frame B w.r.t. frame A at T_i (p. 111)
$\mathcal{MP}_i$: Set of Manipulation Primitive parameters at T_i (p. 109)
n : Number of sensor systems (p. 112)
${}^r\vec{o}_i^c$: Control variable vectors with $r \in \{pos, vel, acc\}$ (p. 120)
${}^r\mathbf{O}_i^c$: Controller output matrices with $r \in \{pos, vel, acc\}$ (p. 120)
RF_i : Reference frame of the Task Frame at T_i (p. 110)
$\mathbb{R}$: Set of real numbers (p. 110)
$\mathbf{S}_i^c$: Classical selection matrix for one controller c (p. 117)
$\mathcal{S}$: Set of sensor signals (p. 123)
τ_i : Tool command of a manipulation primitive $\mathcal{MP}_i$ at T_i (p. 109)
$\vec{\theta}_i$: Cartesian pose vector with six elements: ${}_x\theta_i, {}_y\theta_i, {}_z\theta_i, {}_x\theta_i, {}_y\theta_i, {}_z\theta_i$ (p. 110)
$\mathcal{TF}_i$: Task Frame parameters of a hybrid move command $\mathcal{HM}_i$ at T_i (p. 110)
WF : World frame (updated by the system every control cycle) (p. 110)
$\mathbf{Z}_i^c$: Allocation matrix for controller c at T_i (p. 119)

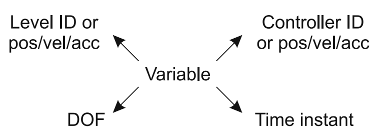

Fig. S.4 Convention for sub- and superscripts of variables and values in a hybrid switched-system.

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