Problem Formulation

$$
\begin{aligned}
& && \texttt{/* Cost Function */} \\
&\min_{x(\cdot),\, u(\cdot),\, z(\cdot),\, s(\cdot),\, s^{\mathrm{e}}} && \int_0^T l(x(\tau), u(\tau), z(\tau), p) + \frac{1}{2} \begin{bmatrix} s_{\mathrm{l}}(\tau) \\ s_{\mathrm{u}}(\tau) \\ 1 \end{bmatrix}^\top \begin{bmatrix} Z_{\mathrm{l}} & 0 & z_{\mathrm{l}} \\ 0 & Z_{\mathrm{u}} & z_{\mathrm{u}} \\ z_{\mathrm{l}}{}^\top & z_{\mathrm{u}}{}^\top & 0 \end{bmatrix} \begin{bmatrix} s_{\mathrm{l}}(\tau) \\ s_{\mathrm{u}}(\tau) \\ 1 \end{bmatrix} \mathrm{d}\tau + \\
& && \quad m(x(T), z(T), p) + \frac{1}{2} \begin{bmatrix} s_{\mathrm{l}}^{\mathrm{e}} \\ s_{\mathrm{u}}^{\mathrm{e}} \\ 1 \end{bmatrix}^\top \begin{bmatrix} Z_{\mathrm{l}}^{\mathrm{e}} & 0 & z_{\mathrm{l}}^{\mathrm{e}} \\ 0 & Z_{\mathrm{u}}^{\mathrm{e}} & z_{\mathrm{u}}^{\mathrm{e}} \\ z_{\mathrm{l}}^{\mathrm{e}\top} & z_{\mathrm{u}}^{\mathrm{e}\top} & 0 \end{bmatrix} \begin{bmatrix} s_{\mathrm{l}}^{\mathrm{e}} \\ s_{\mathrm{u}}^{\mathrm{e}} \\ 1 \end{bmatrix} \\
& && \texttt{/* Initial value */} \\
&\text{s.t.} && x(0) - \bar{x}_0 = 0, \\
& && \texttt{/* Dynamics */} \\
& && f_{\mathrm{impl}}(x(t), \dot{x}(t), u(t), z(t), p) = 0, && t \in [0,\, T), \\
& && \texttt{/* Path Constraints with lower bound */} \\
& && \underline{h} \leq h(x(t), u(t), p) + J_{\mathrm{sh}} s_{\mathrm{l,h}}(t), && t \in [0,\, T), \\
& && \underline{x} \leq J_{\mathrm{bx}} x(t) + J_{\mathrm{sbx}} s_{\mathrm{l,bx}}(t), && t \in (0,\, T), \\
& && \underline{u} \leq J_{\mathrm{bu}} u(t) + J_{\mathrm{sbu}} s_{\mathrm{l,bu}}(t), && t \in [0,\, T), \\
& && \underline{g} \leq C x(t) + D u(t) + J_{\mathrm{sg}} s_{\mathrm{l,g}}(t), && t \in [0,\, T), \\
& && s_{\mathrm{l,h}}(t), s_{\mathrm{l,bx}}(t), s_{\mathrm{l,bu}}(t), s_{\mathrm{l,g}}(t) \geq 0, && t \in [0,\, T), \\
& && \texttt{/* Path Constraints with upper bound */} \\
& && h(x(t), u(t), p) - J_{\mathrm{sh}} s_{\mathrm{u,h}}(t) \leq \bar{h}, && t \in [0,\, T), \\
& && J_{\mathrm{bx}} x(t) - J_{\mathrm{sbx}} s_{\mathrm{u,bx}}(t) \leq \bar{x}, && t \in (0,\, T), \\
& && J_{\mathrm{bu}} u(t) - J_{\mathrm{sbu}} s_{\mathrm{u,bu}}(t) \leq \bar{u}, && t \in [0,\, T), \\
& && C x(t) + D u(t) - J_{\mathrm{sg}} s_{\mathrm{u,g}} \leq \bar{g}, && t \in [0,\, T), \\
& && s_{\mathrm{u,h}}(t), s_{\mathrm{u,bx}}(t), s_{\mathrm{u,bu}}(t), s_{\mathrm{u,g}}(t) \geq 0, && t \in [0,\, T), \\
& && \texttt{/* Terminal Constraints with lower bound */} \\
& && \underline{h}^{\mathrm{e}} \leq h^{\mathrm{e}}(x(T), p) + J_{\mathrm{sh}}^{\mathrm{e}} s_{\mathrm{l,h}}^{\mathrm{e}}, \\
& && \underline{x}^{\mathrm{e}} \leq J_{\mathrm{bx}}^{\mathrm{e}} x(T) + J_{\mathrm{sbx}} s_{\mathrm{l,bx}}^{\mathrm{e}}, \\
& && \underline{g}^{\mathrm{e}} \leq C^{\mathrm{e}} x(T) + J_{\mathrm{sg}}^{\mathrm{e}} s_{\mathrm{l,g}}^{\mathrm{e}} \leq \bar{g}^{\mathrm{e}}, \\
& && s_{\mathrm{l,h}}^{\mathrm{e}}, s_{\mathrm{l,bx}}^{\mathrm{e}}, s_{\mathrm{l,bu}}^{\mathrm{e}}, s_{\mathrm{l,g}}^{\mathrm{e}} \geq 0, \\
& && \texttt{/* Terminal Constraints with upper bound */} \\
& && h^{\mathrm{e}}(x(T), p) - J_{\mathrm{sh}}^{\mathrm{e}} s_{\mathrm{h}}^{\mathrm{e}} \leq \bar{h}^{\mathrm{e}}, \\
& && J_{\mathrm{bx}}^{\mathrm{e}} x(T) - J_{\mathrm{sbx}} s_{\mathrm{bx}}^{\mathrm{e}} \leq \bar{x}^{\mathrm{e}}, \\
& && C^{\mathrm{e}} x(T) - J_{\mathrm{sg}}^{\mathrm{e}} s_{\mathrm{g}}^{\mathrm{e}} \leq \bar{g}^{\mathrm{e}} \\
& && s_{\mathrm{u,h}}^{\mathrm{e}}, s_{\mathrm{u,bx}}^{\mathrm{e}}, s_{\mathrm{u,bu}}^{\mathrm{e}}, s_{\mathrm{u,g}}^{\mathrm{e}} \geq 0,
\end{aligned}
$$

with

- state vector $x : \mathbb{R} \to \mathbb{R}^{n_{\mathrm{x}}}$
- control vector $u : \mathbb{R} \to \mathbb{R}^{n_{\mathrm{u}}}$
- algebraic state vector $z : \mathbb{R} \to \mathbb{R}^{n_{\mathrm{z}}}$
- model parameters $p \in \mathbb{R}^{n_{\mathrm{p}}}$
- slacks for path constraints $s_{\mathrm{l}}(t) = (s_{\mathrm{l,bu}}, s_{\mathrm{l,bx}}, s_{\mathrm{l,g}}, s_{\mathrm{l,h}}) \in \mathbb{R}^{n_{\mathrm{s}}}$ and $s_{\mathrm{u}}(t) = (s_{\mathrm{u,bu}}, s_{\mathrm{u,bx}}, s_{\mathrm{u,g}}, s_{\mathrm{u,h}}) \in \mathbb{R}^{n_{\mathrm{s}}}$
- slacks for terminal constraints $s_{\mathrm{l}}^{\mathrm{e}}(t) = (s_{\mathrm{l,bx}}^{\mathrm{e}}, s_{\mathrm{l,g}}^{\mathrm{e}}, s_{\mathrm{l,h}}^{\mathrm{e}}) \in \mathbb{R}^{n_{\mathrm{s}}^{\mathrm{e}}}$ and $s_{\mathrm{u}}^{\mathrm{e}}(t) = (s_{\mathrm{u,bx}}^{\mathrm{e}}, s_{\mathrm{u,g}}^{\mathrm{e}}, s_{\mathrm{u,h}}^{\mathrm{e}}) \in \mathbb{R}^{n_{\mathrm{s}}^{\mathrm{e}}}$

1 Dynamics

The function $f_{\mathrm{impl}} : \mathbb{R}^{n_{\mathrm{x}}} \times \mathbb{R}^{n_{\mathrm{x}}} \times \mathbb{R}^{n_{\mathrm{u}}} \times \mathbb{R}^{n_{\mathrm{z}}} \times \mathbb{R}^{n_{\mathrm{p}}} \to \mathbb{R}^{n_{\mathrm{x}}+n_{\mathrm{z}}}$ describes the dynamics as a fully implicit DAE.
We offer to discretize F with a classic implicit Runge-Kutta (`irk`) or a structure exploiting implicit Runge-Kutta method (`irk_gnsf`).
Additionally, we offer an explicit Runge-Kutta integrator (`erk`), which can be used with explicit ODE models, i.e. models of the form

$$f_{\mathrm{expl}}(x, u, p) = \dot{x}$$

Mathematical Expression	string identifier	data type	required
f_{impl} respectively f_{expl}	`dyn_expr_f`	`CasADi` expression	yes
-	`dyn_type`	string (`explicit` or `implicit`)	yes

2 Cost

There are different `acados` modules to model the cost functions.

- $l : \mathbb{R}^{n_{\mathrm{x}}} \times \mathbb{R}^{n_{\mathrm{u}}} \times \mathbb{R}^{n_{\mathrm{z}}} \to \mathbb{R}$ is the Lagrange objective term.
- $m : \mathbb{R}^{n_{\mathrm{x}}} \times \mathbb{R}^{n_{\mathrm{z}}} \to \mathbb{R}$ is the Mayer objective term.

to decide which one is used set `cost_type` for l, `cost_type_e` for m.

Setting the slack penalties is done in the same way for all cost modules, namely:

Mathematical Expression	string identifier	data type	required
Z_{l}	`cost_Zl`	double	no
Z_{u}	`cost_Zu`	double	no
z_{l}	`cost_zl`	double	no
z_{u}	`cost_zu`	double	no
$Z_{\mathrm{l}}^{\mathrm{e}}$	`cost_Zl_e`	double	no
$Z_{\mathrm{u}}^{\mathrm{e}}$	`cost_Zu_e`	double	no
$z_{\mathrm{l}}^{\mathrm{e}}$	`cost_zl_e`	double	no
$z_{\mathrm{u}}^{\mathrm{e}}$	`cost_zu_e`	double	no

Moreover, you can specify `cost_Z`, to set $Z_{\mathrm{l}}, Z_{\mathrm{u}}$ to the same values, i.e. use a symmetric L2 slack penalty. Similarly, `cost_z`, `cost_Z_e`, `cost_z_e` can be used to set symmetric slack L1 penalties, respectively penalties for the terminal slack variables.

Cost module: `auto`

Set `cost_type` to `auto` (default). In this case we detect if the cost function specified is a linear least squares term and transcribe it in the corresponding form. Otherwise, it is formulated using the external cost module. Note: slack penalties are optional and we plan to detected them form the expressions in future versions.

Mathematical Expression	string identifier	data type	required
l	`cost_expr_ext_cost`	`CasADi` expression	yes
m	`cost_expr_ext_cost_e`	`CasADi` expression	yes

Cost module: `external`

Set `cost_type` to `ext_cost`.

Mathematical Expression	string identifier	data type	required
l	`cost_expr_ext_cost`	`CasADi` expression	yes
m	`cost_expr_ext_cost_e`	`CasADi` expression	yes

Cost module: `linear least squares`

Set `cost_type` to `linear_ls`.
The Lagrange cost term has the form

$$l(x,u,z) = \frac{1}{2}\left\|\underbrace{V_x x + V_u u + V_z z}_{y} - y_{\mathrm{ref}}\right\|_W^2$$

with matrices V_x, V_u, V_z, W of appropriate dimensions.
Similarly, the Mayer cost term has the form

$$m(x,u,z) = \frac{1}{2}\left\|\underbrace{V_x^{\mathrm{e}} x}_{y^{\mathrm{e}}} - y_{\mathrm{ref}}^{\mathrm{e}}\right\|_{W^{\mathrm{e}}}^2$$

with matrices $V_x^{\mathrm{e}}, W^{\mathrm{e}}$ of appropriate dimensions.

Mathematical Expression	string identifier	data type	required
V_x	`cost_V_x`	double	yes
V_u	`cost_V_u`	double	yes
V_z	`cost_V_z`	double	yes
W	`cost_W`	double	yes
y_{ref}	`cost_y_ref`	double	yes
V_x^{e}	`cost_V_x_e`	double	yes
W^{e}	`cost_W_e`	double	yes
$y_{\mathrm{ref}}^{\mathrm{e}}$	`cost_y_ref_e`	double	yes

Cost module: `nonlinear least squares`

Set `cost_type` to `nonlinear_ls`.
The cost function has the same form as in the linear least squares module.
The only difference is that y, respectively y^{e} are defined as `CasADi` expressions, instead of the matrices V_x, V_u, V_z, respectively V_x^{e}

Mathematical Expression	string identifier	data type	required
y	`cost_expr_y`	`CasADi` expression	yes
W	`cost_W`	double	yes
y_{ref}	`cost_y_ref`	double	yes
y^{e}	`cost_expr_y_e`	`CasADi` expression	yes
$y_{\mathrm{ref}}^{\mathrm{e}}$	`cost_y_ref_e`	double	yes

3 Constraints

3.1 Initial State

Note: An initial state is not required. For example for MHE problems it should not be set.

Mathematical Expression	string identifier	data type	required
$\bar{x}_0$	`constr_x0`	double	no

3.2 Path Constraints

Mathematical Expression	string identifier	data type	required
J_{bx}	`constr_Jbx`	double	no
$\underline{x}$	`constr_lbx`	double	no
$\bar{x}$	`constr_ubx`	double	no
J_{bu}	`constr_Jbu`	double	no
$\underline{u}$	`constr_lbu`	double	no
$\bar{u}$	`constr_ubu`	double	no
C	`constr_C`	double	no
D	`constr_D`	double	no
$\underline{g}$	`constr_lg`	double	no
$\bar{g}$	`constr_ug`	double	no
h	`constr_expr_h`	`CasADi` expression	no
$\underline{h}$	`constr_lh`	double	no
$\bar{h}$	`constr_uh`	double	no
J_{sbx}	`constr_Jsbx`	double	no
J_{sbu}	`constr_Jsbu`	double	no
J_{sg}	`constr_Jsg`	double	no
J_{sbx}	`constr_Jsh`	double	no

3.3 Terminal Constraints

Mathematical Expression	string identifier	data type	required
J_{bx}	constr_Jbx_e	double	no
$\underline{x}^{\mathrm{e}}$	constr_lbx_e	double	no
$\bar{x}^{\mathrm{e}}$	constr_ubx_e	double	no
C^{e}	constr_C_e	double	no
$\underline{g}^{\mathrm{e}}$	constr_lg	double	no
$\bar{g}^{\mathrm{e}}$	constr_ug	double	no
h^{e}	constr_expr_h_e	CasADi expression	no
$\underline{h}^{\mathrm{e}}$	constr_lh_e	double	no
$\bar{h}^{\mathrm{e}}$	constr_uh_e	double	no
J_{sbx}	constr_Jsbx	double	no
$J_{\mathrm{sg}}^{\mathrm{e}}$	constr_Jsg_e	double	no
$J_{\mathrm{sbx}}^{\mathrm{e}}$	constr_Jsh_e	double	no