Cubic B-spline based walk generator

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1 Cubic B splines

Let

- m be an integer bigger than 7,
- $t_0 \leq t_1 \leq \cdots \leq t_{m-1}$ an increasing sequence of real values,
- $\mathbf{x}_i \in \mathbb{R}^2, 0 \leq i \leq m-5$ control points in the plane.

We define the curve $\mathbf{x}$ from interval $[t_3, t_{m-4}]$ in $\mathbb{R}^2$ as

$$\mathbf{x} = \sum_{i=0}^{m-5} b_{i,3}\mathbf{x}_i \quad (1)$$

where $b_{i,3}$ are the basis function of cubic B splines:

$$\begin{aligned} b_{i,3} &= (B_{i,i}\mathbb{I}_{[t_i,t_{i+1})} + B_{i,i+1}\mathbb{I}_{[t_{i+1},t_{i+2})} + B_{i,i+2}\mathbb{I}_{[t_{i+2},t_{i+3})} + B_{i,i+3}\mathbb{I}_{[t_{i+3},t_{i+4})}) \\ & \quad i = 0, \ldots, m-5 \end{aligned}$$

with

$$\begin{aligned}
B_{i,i}(t) &= \frac{(t-t_i)^3}{(t_{i+3}-t_i)(t_{i+2}-t_i)(t_{i+1}-t_i)} \\
B_{i,i+1}(t) &= \frac{(t-t_i)^2(t_{i+2}-t)}{(t_{i+3}-t_i)(t_{i+2}-t_{i+1})(t_{i+2}-t_i)} + \frac{(t-t_i)(t_{i+3}-t)(t-t_{i+1})}{(t_{i+3}-t_i)(t_{i+3}-t_{i+1})(t_{i+2}-t_{i+1})} \\
&\quad + \frac{(t_{i+4}-t)(t-t_{i+1})^2}{(t_{i+4}-t_{i+1})(t_{i+3}-t_{i+1})(t_{i+2}-t_{i+1})} \\
B_{i,i+2}(t) &= \frac{(t-t_i)(t_{i+3}-t)^2}{(t_{i+3}-t_i)(t_{i+3}-t_{i+1})(t_{i+3}-t_{i+2})} + \frac{(t_{i+4}-t)(t-t_{i+1})(t_{i+3}-t)}{(t_{i+4}-t_{i+1})(t_{i+3}-t_{i+1})(t_{i+3}-t_{i+2})} \\
&\quad + \frac{(t_{i+4}-t)^2(t-t_{i+2})}{(t_{i+4}-t_{i+1})(t_{i+4}-t_{i+2})(t_{i+3}-t_{i+2})} \\
B_{i,i+3}(t) &= \frac{(t_{i+4}-t)^3}{(t_{i+4}-t_{i+1})(t_{i+4}-t_{i+2})(t_{i+4}-t_{i+3})}
\end{aligned}$$

and for any interval I of $\mathbb{R}$, $\mathbb{I}_I$ is the function equal to 1 over I and to 0 outside I.

2 Trajectory of the center of mass

2.1 Input

The input of the walk generator is a sequence of time-stamped steps defined as follows:

1. p is a positive integer not smaller than 3,
2. $\tau_0, \tau_1, \cdots, \tau_{2p-3}$ is an increasing sequence of real values,
3. $\mathbf{s}_0, \mathbf{s}_1, \cdots, \mathbf{s}_{p-1}$ is a sequence of p elements of $\mathbb{R}^2$ representing the successive positions of the foot centers.
4. $\mathbf{c}_{init} \in \mathbb{R}^2$ is the initial position of the center of mass at time τ_0,
5. $\mathbf{c}_{final} \in \mathbb{R}^2$ is the final position of the center of mass at time τ_{2p-3}.

2.2 Reference trajectory of the center of pressure

We define a reference trajectory of the center of pressure called $\mathbf{zmp}_{ref}$ as a continuous piecewise affine curve as follows:

$$
\begin{array}{rcl}
\mathbf{zmp}_{ref}(\tau_0) & = & \mathbf{c}_{init} \\
\mathbf{zmp}_{ref}(\tau_1) & = & \mathbf{s}_1 \\
\mathbf{zmp}_{ref}(\tau_2) & = & \mathbf{s}_1 \\
\mathbf{zmp}_{ref}(\tau_3) & = & \mathbf{s}_2 \\
\vdots & \vdots & \vdots \\
\mathbf{zmp}_{ref}(\tau_{2p-5}) & = & \mathbf{s}_{p-2} \\
\mathbf{zmp}_{ref}(\tau_{2p-4}) & = & \mathbf{s}_{p-2} \\
\mathbf{zmp}_{ref}(\tau_{2p-3}) & = & \mathbf{c}_{final}
\end{array}
$$

such that $\mathbf{zmp}_{ref}$ restricted to each interval $[\tau_i, \tau_{i+1}]$ with $i \in \{0, 1, \cdots, 2p-4\}$ is affine.

2.3 Trajectory of the center of mass

We restrict the trajectory of the center of mass to be a cubic-spline defined by Equation (1). We want

- the whole center of mass trajectory to be defined on interval $[\tau_0, \tau_{2p-3}]$, and
- $l \geq 1$ knots on each interval $[\tau_i, \tau_{i+1})$, $i \in \{0, \cdots, 2p-3\}$.

We get the following relations between the various parameters:

$$\begin{aligned} m &= (2p-3)l+7 \\ t_3 &= \tau_0 \\ t_{m-4} &= \tau_{2p-3} \end{aligned}$$

We set
$$\begin{aligned} t_0 &= \tau_0 - 3 \\ t_1 &= \tau_0 - 2 \\ t_2 &= \tau_0 - 1 \end{aligned} \qquad \begin{aligned} t_{m-3} &= \tau_{2p-3} + 1 \\ t_{m-2} &= \tau_{2p-3} + 2 \\ t_{m-1} &= \tau_{2p-3} + 3 \end{aligned}$$

and

$$t_{3+k\,l+j} = \frac{l-j}{l}\,\tau_k + \frac{j}{l}\,\tau_{k+1} \text{ for } j \in \{0, \cdots, l-1\},\ k \in \{0, \cdots, 2p-4\}$$

2.4 Trajectory of the center of pressure

Let g be the gravity constant, and z the constant height of the center of mass. By denoting $\omega = \sqrt{g/z}$, we get the simplified formula for the center of pressure of the robot:

$$\mathbf{zmp} = \mathbf{x} - \frac{1}{\omega^2}\ddot{\mathbf{x}}$$

By setting

$$z_{i,3} \triangleq b_{i,3} - \frac{1}{\omega^2}\ddot{b}_{i,3}$$

we get an expression of the center of pressure with respect to the control points of the cubic B spline:

$$\mathbf{zmp} = \sum_{i=0}^{m-5} z_{i,3}\mathbf{x}_i = \sum_{i=0}^{2p-1} z_{i,3}\mathbf{x}_i \tag{2}$$

2.5 Optimal control problem

We denote by $X = (\mathbf{x}_0, \cdots, \mathbf{x}_{m-5})$ the vector of control points. We wish to find the cubic B spline trajectory that minimizes the following cost function:

$$C(X) \triangleq \frac{1}{2}\int_{\tau_0}^{\tau_{2p-3}} \|\mathbf{zmp}(t) - \mathbf{zmp}_{ref}(t)\|^2 dt \tag{3}$$

Let us expand this formula using (2):

$$
\begin{aligned}
C(X) &= \frac{1}{2}\int_{\tau_0}^{\tau_{2p-3}} (\sum_{i=0}^{2p-4} z_{i,3}\mathbf{x}_i - \mathbf{zmp}_{ref}(t))^T(\sum_{i=0}^{2p-4} z_{i,3}\mathbf{x}_i - \mathbf{zmp}_{ref}(t))dt \\
&= \frac{1}{2}\sum_{i=0}^{m-5}\sum_{j=0}^{m-5}\int_{\tau_0}^{\tau_{2p-3}} z_{i,3}z_{j,3}(t)dt\ \mathbf{x}_i^T\mathbf{x}_j - \sum_{i=0}^{m-5}\int_{\tau_0}^{\tau_{2p-3}} z_{i,3}\mathbf{zmp}_{ref}^T(t)dt\ \mathbf{x}_i \\
&\quad + \int_{\tau_0}^{\tau_{2p-3}} \mathbf{zmp}_{ref}^T\mathbf{zmp}_{ref}(t)dt
\end{aligned}
$$

The cost function can be rewritten as

$$
C(X) = \frac{1}{2}X^THX - b^TX + C_0
$$

with

$$
\begin{aligned}
H &= \left(\int_{\tau_0}^{\tau_{2p-3}} z_{i,3}z_{j,3}(t)dt\ I_2 \right)_{i,j=0,\cdots,m-5} \\
b &= \left(\int_{\tau_0}^{\tau_{2p-3}} z_{i,3}\mathbf{zmp}_{ref}(t)dt \right)_{i=0,\cdots,m-5} \\
C_0 &= \int_{\tau_0}^{\tau_{2p-3}} \mathbf{zmp}_{ref}^T\mathbf{zmp}_{ref}(t)dt
\end{aligned}
$$

$C(X)$ is the sum of two terms that respectively depend on the x and y coordinates of the control points. Let us denote $\mathbf{x}_{i,0}$, $\mathbf{x}_{i,1}$ the abscissa and the ordinate of $\mathbf{x}_i$, $\mathbf{zmp}_{ref\,0}$, $\mathbf{zmp}_{ref\,1}$ the abscissa and ordinate of $\mathbf{zmp}_{ref}$, and let us define

$$
\begin{aligned}
X_0 &= (\mathbf{x}_{0,0}, \cdots, \mathbf{x}_{m-5,0}) \\
X_1 &= (\mathbf{x}_{0,1}, \cdots, \mathbf{x}_{m-5,1}) \\
b_0 &= \left(\int_{\tau_0}^{\tau_{2p-3}} z_{i,3}\ \mathbf{zmp}_{ref\,0}(t)dt \right)_{i=0,\cdots,m-5} \\
b_1 &= \left(\int_{\tau_0}^{\tau_{2p-3}} z_{i,3}\ \mathbf{zmp}_{ref\,1}(t)dt \right)_{i=0,\cdots,m-5} \\
H_0 = H_1 &= \left(\int_{\tau_0}^{\tau_{2p-3}} z_{i,3}z_{j,3}(t)dt \right)_{i,j=0,\cdots,m-5}
\end{aligned}
$$

Then,

$$
C(X) = \frac{1}{2}X_0^TH_0X_0 - b_0^TX_0 + \frac{1}{2}X_1^TH_1X_1 - b_1^TX_1 + C_0
$$

The problem can therefore be decomposed into two decoupled sub-problems, one in X_0 and the other one in X_1.

2.5.1 Linear constraints

Boundary conditions can be added as a constraint on the value of the trajectory of the center of mass and its derivative at a given parameter – usually at the beginning or at the end of the definition interval. Each of these constraints is defined by a tuple $(t, \mathbf{y}, \dot{\mathbf{y}}) \in [\tau_0, \tau_{2p-3}] \times \mathbb{R}^2 \times \mathbb{R}^2$ and is linear in the vector of control points.

$$\sum_{i=0}^{m-5} b_{i,3}(t)\,\mathbf{x}_i = \mathbf{y} \tag{4}$$

$$\sum_{i=0}^{m-5} \dot{b}_{i,3}(t)\,\mathbf{x}_i = \dot{\mathbf{y}} \tag{5}$$

These constraints can be translated to each sub-problem as follows:

$$\begin{aligned} A_0\,X_0 &= c_0 \\ A_1\,X_1 &= c_1 \end{aligned}$$

with

$$\begin{aligned} A_0 = A_1 &\triangleq \begin{pmatrix} b_{0,3}(t) & b_{1,3}(t) & \cdots & b_{m-5,3}(t) \\ \dot{b}_{0,3}(t) & \dot{b}_{1,3}(t) & \cdots & \dot{b}_{m-5,3}(t) \end{pmatrix} \\ c_0 &= \begin{pmatrix} \mathbf{y}_0 \\ \dot{\mathbf{y}}_0 \end{pmatrix} \\ c_1 &= \begin{pmatrix} \mathbf{y}_1 \\ \dot{\mathbf{y}}_1 \end{pmatrix} \end{aligned}$$

2.5.2 Resolution of the quadratic program

The constrained problem can be expressed as follows for $i \in 0, 1$:

$$\min_{X_i} \frac{1}{2} X_i^T H_i X_i - b_i^T X_i \quad \text{such that} \quad A_i\,X = c_i$$

using the singular value decomposition of A_i

$$A_i = \begin{pmatrix} U_1 & U_0 \end{pmatrix} \Sigma \begin{pmatrix} V_1 & V_0 \end{pmatrix}^T$$

we get a parameterization of the affine sub-space defined by the constraint:

$$X_i = X_{i\,0} + V_0 \mathbf{u} \quad \mathbf{u} \in \mathbb{R}^{m-4-rank(A_i)}$$

where $X_{i\,0} = A_i^+ c_i$. Solving the constrained QP consists in finding $\mathbf{u}$ that minimizes

$$\begin{aligned} & \frac{1}{2}(X_{i\,0} + V_0\mathbf{u})^T H_i (X_{i\,0} + V_0\mathbf{u}) - b_i^T (X_{i\,0} + V_0\mathbf{u}) \\ = \; & \frac{1}{2}\mathbf{u}^T V_0^T H_i V_0 \mathbf{u} + X_{i\,0}^T H_i V_0 \mathbf{u} - b_i^T V_0 \mathbf{u} + Cste \\ = \; & \frac{1}{2}\mathbf{u}^T V_0^T H_i V_0 \mathbf{u} + (V_0^T H_i X_{i\,0} - V_0^T b_i)^T \mathbf{u} + Cste \end{aligned}$$

The value of $\mathbf{u}$ that minimizes the above expression is given by

$$\mathbf{u_i}^* = (V_0^T H_i V_0)^{-1}(V_0^T b_i - V_0^T H_i X_{i\,0})$$

2.6 Computation of the coefficients

$$\begin{aligned} z_{i,3} &= (Z_{i,i}\mathbb{I}_{[t_i,t_{i+1})} + Z_{i,i+1}\mathbb{I}_{[t_{i+1},t_{i+2})} + Z_{i,i+2}\mathbb{I}_{[t_{i+2},t_{i+3})} + Z_{i,i+3}\mathbb{I}_{[t_{i+3},t_{i+4})}) \\ & \quad i = 0, \ldots, m-5 \end{aligned}$$

with

$$\begin{aligned} Z_{i,i}(t) &= B_{i,i} - \frac{1}{\omega^2}\ddot{B}_{i,i} \\ Z_{i,i+1}(t) &= B_{i,i+1} - \frac{1}{\omega^2}\ddot{B}_{i,i+1} \\ Z_{i,i+2}(t) &= B_{i,i+2} - \frac{1}{\omega^2}\ddot{B}_{i,i+2} \\ Z_{i,i+3}(t) &= B_{i,i+3} - \frac{1}{\omega^2}\ddot{B}_{i,i+3} \end{aligned}$$

Matrix H_0 is symmetric. For any integer i such that $0 \leq i \leq m-5$, and any non-negative integer k, such that $k \leq 3$ and $i+k \leq m-5$, The coefficient $(i, i+k)$ of matrix H_0, with $k \in \{0,1,2,3\}$ is equal to

$$\begin{aligned} H_{0\ i,i+k} &= \int_{\tau_0}^{\tau_{2p-3}} z_{i,3} z_{i+k,3}(t)dt \\ &= \sum_{j=0}^{3-k} \int_{t_{i+k+j}}^{t_{i+k+j+1}} Z_{i,i+k+j} Z_{i+k,i+k+j}(t)dt \end{aligned}$$

The coefficients of vector b_0 are equal to:

$$\begin{aligned} b_{0\,i} &= \int_{t_3}^{t_{m-4}} (Z_{i,i}\mathbb{I}_{[t_i,t_{i+1})} + Z_{i,i+1}\mathbb{I}_{[t_{i+1},t_{i+2})} + Z_{i,i+2}\mathbb{I}_{[t_{i+2},t_{i+3})} + Z_{i,i+3}\mathbb{I}_{[t_{i+3},t_{i+4})})\, \mathbf{zmp}_{ref\,i}(t)dt \\ &= \sum_{j=\max(0,3-i)}^{\min(3,m-5-i)} \int_{t_{i+j}}^{t_{i+j+1}} Z_{i,i+j}\mathbf{zmp}_{ref\,i}(t)\,dt \end{aligned}$$

Special cases for boundary conditions

If $t = \tau_0 = t_3$,

$$A_0 = A_1 = \begin{pmatrix} B_{0,0+3}(t_3) & B_{1,1+2}(t_3) & B_{2,2+1}(t_3) & 0 & \cdots & 0 \\ \dot{B}_{0,0+3}(t_3) & \dot{B}_{1,1+2}(t_3) & \dot{B}_{2,2+1}(t_3) & 0 & \cdots & 0 \end{pmatrix}$$

If $t = \tau_{2p-3} = t_{m-4}$

$$A_0 = A_1 = \begin{pmatrix} 0 & \cdots & 0 & B_{m-7,m-4}(t_{m-4}) & B_{m-6,m-4}(t_{m-4}) & B_{m-5,m-4}(t_{m-4}) \\ 0 & \cdots & 0 & \dot{B}_{m-7,m-4}(t_{m-4}) & \dot{B}_{m-6,m-4}(t_{m-4}) & \dot{B}_{m-5,m-4}(t_{m-4}) \end{pmatrix}$$

3 Trajectory of the feet

We define the trajectories of the feet as piece-wise polynomial curves of degree 3. Let us recall that for any polynomial function P of degree 3 and any $t \in \mathbb{R}$, we have

$$\begin{aligned} P(t) \quad = \quad & \Big(2P(0) - 2P(1) + \dot{P}(0) + \dot{P}(1)\Big)\ t^3 \\ & + \Big(-3P(0) + 3P(1) - 2\dot{P}(0) - \dot{P}(1)\Big)\ t^2 \\ & + \dot{P}(0)\ t \ + \ P(0) \end{aligned}$$