

軌道最適化による動作生成 リファレンスマニュアル

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1 軌道最適化による動作生成の基礎

1.1 タスク関数のノルムを最小にするコンフィギュレーションの探索

$q \in \mathbb{R}^{n_q}$ を設計対象のコンフィギュレーションとする．例えば一般の逆運動学計算では， q はある瞬間のロボットの関節角度を表すベクトルで，コンフィギュレーションの次元 n_q はロボットの関節自由度数となる．

動作生成問題を，所望のタスクに対応するタスク関数 $e(q) : \mathbb{R}^{n_q} \rightarrow \mathbb{R}^{n_e}$ について，次式を満たす q を得ることとして定義する．

$$e(q) = 0 \quad (1.1)$$

例えば一般の逆運動学計算では， $e(q)$ はエンドエフェクタの目標位置姿勢と現在位置姿勢の差を表す 6 次元ベクトルである．非線形方程式 (1.1) の解を解析的に得ることは難しく，反復計算による数値解法が採られる．式 (1.1) が解をもたないときでも最善のコンフィギュレーションを得られるように一般化すると，式 (1.1) の求解は次の最適化問題として表される¹．

$$\min_q F(q) \quad (1.2a)$$

$$\text{where } F(q) \stackrel{\text{def}}{=} \frac{1}{2} \|e(q)\|^2 \quad (1.2b)$$

コンフィギュレーションが最小値 q_{min} と最大値 q_{max} の間に含まれる必要があるとき，逆運動学計算は次の制約付き非線形最適化問題として表される．

$$\min_q F(q) \quad \text{s.t.} \quad q_{min} \leq q \leq q_{max} \quad (1.3)$$

例えば一般の逆運動学計算では， q_{min}, q_{max} は関節角度の許容範囲の最小値，最大値を表す．以降では，式 (1.3) の制約を，より一般の形式である線形等式制約，線形不等式制約として次式のように表す²．

$$\min_q F(q) \quad (1.4a)$$

$$\text{s.t.} \quad Aq = \bar{b} \quad (1.4b)$$

$$Cq \geq \bar{d} \quad (1.4c)$$

制約付き非線形最適化問題の解法のひとつである逐次二次計画法では，次の二次計画問題の最適解として得られる Δq_k^* を用いて， $q_{k+1} = q_k + \Delta q_k^*$ として反復更新することで，式 (1.4) の最適解を導出する³．

$$\min_{\Delta q_k} F(q_k) + \nabla F(q_k)^T \Delta q_k + \frac{1}{2} \Delta q_k^T \nabla^2 F(q_k) \Delta q_k \quad (1.5a)$$

$$\text{s.t.} \quad A \Delta q_k = \bar{b} - Aq_k \quad (1.5b)$$

$$C \Delta q_k \geq \bar{d} - Cq_k \quad (1.5c)$$

¹ 任意の半正定値行列 W に対して， $\|e(q)\|_W^2 = e(q)^T W e(q) = e(q)^T S^T S e(q) = \|S e(q)\|^2$ を満たす S が必ず存在するので，式 (1.2b) は任意の重み付きノルムを表現可能である．

² 式 (1.3) における関節角度の最小値，最大値に関する制約は次式のように表される．

$$\begin{aligned} q_{min} &\leq q \leq q_{max} \\ \Leftrightarrow \begin{pmatrix} I \\ -I \end{pmatrix} q &\geq \begin{pmatrix} q_{min} \\ -q_{max} \end{pmatrix} \end{aligned}$$

³ 式 (1.5a) は $F(q)$ を q_k の周りでテーラー展開し三次以下の項を省略したものに一致する．逐次二次計画法については，以下の書籍の 18 章で詳しく説明されている．

Numerical optimization, S. Wright and J. Nocedal, Springer Science, vol. 35, 1999, http://www.xn--vjq503akpco3w.top/literature/Nocedal_Wright_Numerical_optimization_v2.pdf.

$\nabla F(\mathbf{q}_k), \nabla^2 F(\mathbf{q}_k)$ はそれぞれ, $F(\mathbf{q}_k)$ の勾配, ヘッセ行列⁴で, 次式で表される.

$$\nabla F(\mathbf{q}) = \left(\frac{\partial e(\mathbf{q})}{\partial \mathbf{q}} \right)^T e(\mathbf{q}) \quad (1.6a)$$

$$= \mathbf{J}(\mathbf{q})^T e(\mathbf{q}) \quad (1.6b)$$

$$\nabla^2 F(\mathbf{q}) = \sum_{i=1}^m e_i(\mathbf{q}) \nabla^2 e_i(\mathbf{q}) + \left(\frac{\partial e(\mathbf{q})}{\partial \mathbf{q}} \right)^T \frac{\partial e(\mathbf{q})}{\partial \mathbf{q}} \quad (1.6c)$$

$$\approx \left(\frac{\partial e(\mathbf{q})}{\partial \mathbf{q}} \right)^T \frac{\partial e(\mathbf{q})}{\partial \mathbf{q}} \quad (1.6d)$$

$$= \mathbf{J}(\mathbf{q})^T \mathbf{J}(\mathbf{q}) \quad (1.6e)$$

ただし, $e_i(\mathbf{q})$ ($i = 1, 2, \dots, m$) は $e(\mathbf{q})$ の i 番目の要素である. 式 (1.6c) から式 (1.6d) への変形では $e(\mathbf{q})$ の二階微分がゼロであると近似している. $\mathbf{J}(\mathbf{q}) \stackrel{\text{def}}{=} \frac{\partial e(\mathbf{q})}{\partial \mathbf{q}} \in \mathbb{R}^{n_e \times n_q}$ は $e(\mathbf{q})$ のヤコビ行列である.

式 (1.6a), 式 (1.6d) から式 (1.5a) の目的関数は次式で表される⁵.

$$\frac{1}{2} \mathbf{e}_k^T \mathbf{e}_k + \mathbf{e}_k^T \mathbf{J}_k \Delta \mathbf{q}_k + \frac{1}{2} \Delta \mathbf{q}_k^T \mathbf{J}_k^T \mathbf{J}_k \Delta \mathbf{q}_k \quad (1.7a)$$

$$= \frac{1}{2} \|\mathbf{e}_k + \mathbf{J}_k \Delta \mathbf{q}_k\|^2 \quad (1.7b)$$

ただし, $\mathbf{e}_k \stackrel{\text{def}}{=} e(\mathbf{q}_k), \mathbf{J}_k \stackrel{\text{def}}{=} \mathbf{J}(\mathbf{q}_k)$ とした.

結局, 逐次二次計画法で反復的に解かれる二次計画問題 (1.5) は次式で表される.

$$\min_{\Delta \mathbf{q}_k} \frac{1}{2} \Delta \mathbf{q}_k^T \mathbf{J}_k^T \mathbf{J}_k \Delta \mathbf{q}_k + \mathbf{e}_k^T \mathbf{J}_k \Delta \mathbf{q}_k \quad (1.8a)$$

$$\text{s.t. } \mathbf{A} \Delta \mathbf{q}_k = \mathbf{b} \quad (1.8b)$$

$$\mathbf{C} \Delta \mathbf{q}_k \geq \mathbf{d} \quad (1.8c)$$

ここで,

$$\mathbf{b} = \bar{\mathbf{b}} - \mathbf{A} \mathbf{q}_k \quad (1.9)$$

$$\mathbf{d} = \bar{\mathbf{d}} - \mathbf{C} \mathbf{q}_k \quad (1.10)$$

とおいた.

1.2 コンフィギュレーション二次形式の正則化項の追加

式 (1.2a) の最適化問題の目的関数を, 次式の $\hat{F}(\mathbf{q})$ で置き換える.

$$\hat{F}(\mathbf{q}) = F(\mathbf{q}) + F_{reg}(\mathbf{q}) \quad (1.11)$$

$$\text{where } F_{reg}(\mathbf{q}) = \frac{1}{2} \mathbf{q}^T \bar{\mathbf{W}}_{reg} \mathbf{q} \quad (1.12)$$

目的関数 $\hat{F}(\mathbf{q})$ の勾配, ヘッセ行列は次式で表される.

$$\nabla \hat{F}(\mathbf{q}) = \nabla F(\mathbf{q}) + \nabla F_{reg}(\mathbf{q}) \quad (1.13a)$$

$$= \mathbf{J}(\mathbf{q})^T e(\mathbf{q}) + \bar{\mathbf{W}}_{reg} \mathbf{q} \quad (1.13b)$$

$$\nabla^2 \hat{F}(\mathbf{q}) = \nabla^2 F(\mathbf{q}) + \nabla^2 F_{reg}(\mathbf{q}) \quad (1.13c)$$

$$\approx \mathbf{J}(\mathbf{q})^T \mathbf{J}(\mathbf{q}) + \bar{\mathbf{W}}_{reg} \quad (1.13d)$$

⁴式 (1.5a) の $\nabla^2 F(\mathbf{q}_k)$ の部分は一般にはラグランジュ関数の \mathbf{q}_k に関するヘッセ行列であるが, 等式・不等式制約が線形の場合は $F(\mathbf{q}_k)$ のヘッセ行列と等価になる.

⁵式 (1.7b) は, 以下の論文で紹介されている二次計画法によってコンフィギュレーション速度を導出する逆運動学解法における目的関数と一致する.

Feasible pattern generation method for humanoid robots, F. Kanehiro et al., Proceedings of the 2009 IEEE-RAS International Conference on Humanoid Robots, pp. 542-548, 2009.

したがって，式 (1.8) の二次計画問題は次式で表される．

$$\min_{\Delta \mathbf{q}_k} \frac{1}{2} \Delta \mathbf{q}_k^T \left(\mathbf{J}_k^T \mathbf{J}_k + \bar{\mathbf{W}}_{reg} \right) \Delta \mathbf{q}_k + \left(\mathbf{J}_k^T \mathbf{e}_k + \bar{\mathbf{W}}_{reg} \mathbf{q}_k \right)^T \Delta \mathbf{q}_k \quad (1.14a)$$

$$\text{s.t. } \mathbf{A} \Delta \mathbf{q}_k = \mathbf{b} \quad (1.14b)$$

$$\mathbf{C} \Delta \mathbf{q}_k \geq \mathbf{d} \quad (1.14c)$$

1.3 コンフィギュレーション更新量の正則項の追加

Gauss-Newton 法と Levenberg-Marquardt 法の比較を参考に，式 (1.14a) の二次形式項の行列に，次式のよう
に微小な係数をかけた単位行列を加えると，一部の適用例について逐次二次計画法の収束性が改善された⁶．

$$\min_{\Delta \mathbf{q}_k} \frac{1}{2} \Delta \mathbf{q}_k^T \left(\mathbf{J}_k^T \mathbf{J}_k + \bar{\mathbf{W}}_{reg} + \lambda \mathbf{I} \right) \Delta \mathbf{q}_k + \left(\mathbf{J}_k^T \mathbf{e}_k + \bar{\mathbf{W}}_{reg} \mathbf{q}_k \right)^T \Delta \mathbf{q}_k \quad (1.15a)$$

$$\text{s.t. } \mathbf{A} \Delta \mathbf{q}_k = \mathbf{b} \quad (1.15b)$$

$$\mathbf{C} \Delta \mathbf{q}_k \geq \mathbf{d} \quad (1.15c)$$

改良誤差減衰最小二乗法⁷を参考にすると， λ は次式のように決定される．

$$\lambda = \lambda_r F(\mathbf{q}_k) + w_r \quad (1.16)$$

λ_r と w_r は正の定数である．

1.4 ソースコードと数式の対応

$$\mathbf{W}_{reg} \stackrel{\text{def}}{=} \bar{\mathbf{W}}_{reg} + \lambda \mathbf{I} \quad (1.17a)$$

$$\mathbf{v}_{reg} \stackrel{\text{def}}{=} \bar{\mathbf{W}}_{reg} \mathbf{q}_k \quad (1.17b)$$

とすると，式 (1.15) は次式で表される．

$$\min_{\Delta \mathbf{q}_k} \frac{1}{2} \Delta \mathbf{q}_k^T \left(\mathbf{J}_k^T \mathbf{J}_k + \mathbf{W} \right) \Delta \mathbf{q}_k + \left(\mathbf{J}_k^T \mathbf{e}_k + \mathbf{v}_{reg} \right)^T \Delta \mathbf{q}_k \quad (1.18a)$$

$$\text{s.t. } \mathbf{A} \Delta \mathbf{q}_k = \mathbf{b} \quad (1.18b)$$

$$\mathbf{C} \Delta \mathbf{q}_k \geq \mathbf{d} \quad (1.18c)$$

第 2 節や第 4 章で説明する ****-configuration-task* クラスのメソッドは式 (1.18) 中の記号と以下のように対応している．

<i>:config-vector</i>	get \mathbf{q}
<i>:set-config</i>	set \mathbf{q}
<i>:task-value</i>	get $\mathbf{e}(\mathbf{q})$
<i>:task-jacobian</i>	get $\mathbf{J}(\mathbf{q}) \stackrel{\text{def}}{=} \frac{\partial \mathbf{e}(\mathbf{q})}{\partial \mathbf{q}}$
<i>:config-equality-constraint-matrix</i>	get \mathbf{A}
<i>:config-equality-constraint-vector</i>	get \mathbf{b}
<i>:config-inequality-constraint-matrix</i>	get \mathbf{C}
<i>:config-inequality-constraint-vector</i>	get \mathbf{d}
<i>:regular-matrix</i>	get \mathbf{W}_{reg}
<i>:regular-vector</i>	get \mathbf{v}_{reg}

⁶これは，最適化における信頼領域 (trust region) に関連している．

⁷ Levenberg-Marquardt 法による可解性を問わない逆運動学，杉原 知道，日本ロボット学会誌，vol. 29，no. 3，pp. 269-277，2011.

1.5 章の構成

第2章では，コンフィギュレーション q の取得・更新，タスク関数 $e(q)$ の取得，タスク関数のヤコビ行列 $J(q) \stackrel{\text{def}}{=} \frac{\partial e(q)}{\partial q}$ の取得，コンフィギュレーションの等式・不等式制約 A, b, C, d の取得のためのクラスを説明する．第2.1節ではコンフィギュレーション q が瞬時の情報，第2.2節ではコンフィギュレーション q が時系列の情報を表す場合をそれぞれ説明する．

第3章では，第2章で説明されるクラスを用いて逐次二次計画法により最適化を行うためのクラスを説明する．

第4章では，用途に応じて拡張されたコンフィギュレーションとタスク関数のクラスを説明する．第4.1節では，マニピュレーションのために，ロボットに加えて物体のコンフィギュレーションを計画する場合を説明する．第4.2節では，ロボットの関節位置の軌道をBスプライン関数でパラメトリックに表現する場合を説明する．いずれにおいても，最適化では第3章で説明された逐次二次計画法のクラスが利用される．

第5章では，その他の補足事項を説明する．第5.1節では，jskeusで定義されているクラスの拡張について説明する．第5.2節では，環境との接触を有するロボットの問題設定を記述するためのクラスについて説明する．第5.4節では，関節トルクを関節角度で微分したヤコビ行列を導出するための関数について説明する．

2 コンフィギュレーションとタスク関数

2.1 瞬時コンフィギュレーションと瞬時タスク関数

instant-configuration-task

[class]

```

:super      propertied-object
:slots      (_robot-env robot-environment instance)
             (_theta-vector  $\theta$  [rad] [m])
             (_wrench-vector  $\hat{w}$  [N] [Nm])
             (_torque-vector  $\tau$  [Nm])
             (_phi-vector  $\phi$  [rad] [m])
             (_num-kin  $N_{kin} := |\mathcal{T}^{kin-trg}| = |\mathcal{T}^{kin-att}|$ )
             (_num-contact  $N_{cnt} := |\mathcal{T}^{cnt-trg}| = |\mathcal{T}^{cnt-att}|$ )
             (_num-variant-joint  $N_{var-joint} := |\mathcal{J}_{var}|$ )
             (_num-invariant-joint  $N_{invar-joint} := |\mathcal{J}_{invar}|$ )
             (_num-drive-joint  $N_{drive-joint} := |\mathcal{J}_{drive}|$ )
             (_num-posture-joint  $N_{posture-joint} := |\mathcal{J}_{posture}|$ )
             (_num-external  $N_{ex} :=$  number of external wrenches)
             (_num-collision  $N_{col} :=$  number of collision check pairs)
             (_dim-theta  $dim(\theta) = N_{var-joint}$ )
             (_dim-wrench  $dim(\hat{w}) = 6N_{cnt}$ )
             (_dim-torque  $dim(\tau) = N_{drive-joint}$ )
             (_dim-phi  $dim(\phi) = N_{invar-joint}$ )
             (_dim-variant-config  $dim(q_{var})$ )
             (_dim-invariant-config  $dim(q_{invar})$ )
             (_dim-config  $dim(q)$ )
             (_dim-task  $dim(e)$ )
             (_kin-scale-mat-list  $K_{kin}$ )
             (_target-posture-scale  $k_{posture}$ )

```

(_norm-regular-scale-max k_{max})
 (_norm-regular-scale-offset k_{off})
 (_torque-regular-scale k_{trq})
 (_variant-joint-list \mathcal{J}_{var})
 (_invariant-joint-list \mathcal{J}_{invar})
 (_drive-joint-list \mathcal{J}_{drive})
 (_kin-target-coords-list $\mathcal{T}^{kin-trg}$)
 (_kin-attention-coords-list $\mathcal{T}^{kin-att}$)
 (_contact-target-coords-list $\mathcal{T}^{cnt-trg}$)
 (_contact-attention-coords-list $\mathcal{T}^{cnt-att}$)
 (_variant-joint-angle-margin margin of θ [deg] [mm])
 (_invariant-joint-angle-margin margin of ϕ [deg] [mm])
 (_delta-linear-joint trust region of linear joint configuration [mm])
 (_delta-rotational-joint trust region of rotational joint configuration [deg])
 (_contact-constraint-list list of contact-constraint instance)
 (_posture-joint-list $\mathcal{J}_{posture}$)
 (_posture-joint-angle-list $\bar{\theta}^{trg}$)
 (_external-wrench-list $\{\mathbf{w}_1^{ex}, \mathbf{w}_2^{ex}, \dots, \mathbf{w}_{N_{ex}}^{ex}\}$)
 (_external-coords-list $\{T_1^{ex}, T_2^{ex}, \dots, T_{N_{ex}}^{ex}\}$)
 (_collision-pair-list list of bodyset-link or body pair)
 (_collision-distance-margin-list list of collision distance margin)
 (_only-kinematics? whether to consider only kinematics or not)
 (_variant-task-jacobi buffer for $\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{var}}$)
 (_invariant-task-jacobi buffer for $\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{invar}}$)
 (_task-jacobi buffer for $\frac{\partial \mathbf{e}}{\partial \mathbf{q}}$)
 (_collision-theta-inequality-constraint-matrix buffer for $\mathbf{C}_{col, \theta}$)
 (_collision-phi-inequality-constraint-matrix buffer for $\mathbf{C}_{col, \phi}$)
 (_collision-inequality-constraint-vector buffer for \mathbf{C}_{col})

瞬時コンフィギュレーション $\mathbf{q}^{(l)}$ と瞬時タスク関数 $e^{(l)}(\mathbf{q}^{(l)})$ のクラス .

このクラスの説明で用いる全ての変数は、時間ステップ l を表す添字をつけて $x^{(l)}$ と表されるべきだが、このクラス内の説明では省略して x と表す . また、以降では、説明文やメソッド名で、“瞬時” や “instant” を省略する .

コンフィギュレーション \mathbf{q} の取得・更新、タスク関数 $e(\mathbf{q})$ の取得、タスク関数のヤコビ行列 $\frac{\partial e(\mathbf{q})}{\partial \mathbf{q}}$ の取得、コンフィギュレーションの等式・不等式制約 A, b, C, d の取得のためのメソッドが定義されている . コンフィギュレーション・タスク関数を定めるために、初期化時に以下を与える

- ロボット・環境

robot-environment ロボット・環境を表す robot-environment クラスのインスタンス

variant-joint-list \mathcal{J}_{var} 時変関節

invariant-joint-list \mathcal{J}_{invar} 時不変関節 (与えなければ時不変関節は考慮されない)

drive-joint-list \mathcal{J}_{drive} 駆動関節 (与えなければ関節駆動トルクは考慮されない)

- 幾何拘束

kin-target-coords-list $\mathcal{T}^{kin-trg}$ 幾何到達目標位置姿勢リスト

kin-attention-coords-list $\mathcal{T}^{kin-att}$ 幾何到達着目位置姿勢リスト
 kin-scale-mat-list K_{kin} 幾何拘束の座標系, 重みを表す変換行列のリスト

- 接触拘束

contact-target-coords-list $\mathcal{T}^{cnt-trg}$ 接触目標位置姿勢リスト
 contact-attention-coords-list $\mathcal{T}^{cnt-att}$ 接触着目位置姿勢リスト
 contact-constraint-list 接触レンチ制約リスト

- コンフィギュレーション拘束 (必要な場合のみ)

posture-joint-list $\mathcal{J}_{posture}$ 着目関節リスト
 posture-joint-angle-list $\bar{\theta}^{trg}$ 着目関節の目標関節角
 target-posture-scale $k_{posture}$ コンフィギュレーション拘束の重み

- 干渉回避拘束 (必要な場合のみ)

collision-pair-list 干渉回避する bodyset-link もしくは body のペアのリスト
 collision-distance-margin 干渉回避の距離マージン (全てのペアで同じ値の場合)
 collision-distance-margin-list 干渉回避の距離マージンのリスト (ペアごとに異なる値の場合)

- 外レンチ (必要な場合のみ)

external-wrench-list 外レンチのリスト (ワールド座標系で表す)
 external-coords-list 外レンチの作用点座標のリスト (位置のみを使用)

- 目的関数の重み

norm-regular-scale-max k_{max} コンフィギュレーション更新量正則化の重み最大値
 norm-regular-scale-offset k_{off} コンフィギュレーション更新量正則化の重みオフセット
 torque-regular-scale k_{trq} トルク正則化の重み

コンフィギュレーション q は以下から構成される .

$$q := \begin{pmatrix} \theta^T & \hat{w}^T & \tau^T & \phi^T \end{pmatrix}^T \quad (2.1)$$

$\theta \in \mathbb{R}^{N_{var-joint}}$ 時変関節角度 [rad] [m]

$\hat{w} \in \mathbb{R}^{6N_{cnt}}$ 接触レンチ [N] [Nm]

$\tau \in \mathbb{R}^{N_{drive-joint}}$ 関節駆動トルク [Nm] [N]

$\phi \in \mathbb{R}^{N_{invar-joint}}$ 時不変関節角度 [rad] [m]

\hat{w} は次式のように, 全接触部位でのワールド座標系での力・モーメントを並べたベクトルである .

$$\hat{w} = \begin{pmatrix} w_1^T & w_2^T & \cdots & w_{N_{cnt}}^T \end{pmatrix}^T \quad (2.2)$$

$$= \begin{pmatrix} f_1^T & n_1^T & f_2^T & n_2^T & \cdots & f_{N_{cnt}}^T & n_{N_{cnt}}^T \end{pmatrix}^T \quad (2.3)$$

タスク関数 $e(q)$ は以下から構成される .

$$e(q) := \begin{pmatrix} e^{kinT}(q) & e^{eom-transT}(q) & e^{eom-rotT}(q) & e^{trqT}(q) & e^{postureT}(q) \end{pmatrix}^T \quad (2.4)$$

$e^{kin}(q) \in \mathbb{R}^{6N_{kin}}$ 幾何到達拘束 [rad] [m]

$e^{eom-trans}(q) \in \mathbb{R}^3$ 力の釣り合い [N]

$e^{eom-rot}(q) \in \mathbb{R}^3$ モーメントの釣り合い [Nm]

$e^{trq}(q) \in \mathbb{R}^{N_{drive-joint}}$ 関節トルクの釣り合い [rad] [m]

$e^{posture}(\mathbf{q}) \in \mathbb{R}^{N_{posture-joint}}$ 関節角目標 [rad] [m]

:init	<i>ℰkey (name)</i> <i>(robot-env)</i> <i>(variant-joint-list (send robot-env :variant-joint-list))</i> <i>(invariant-joint-list (send robot-env :invariant-joint-list))</i> <i>(drive-joint-list (send robot-env :drive-joint-list))</i> <i>(only-kinematics?)</i> <i>(kin-target-coords-list)</i> <i>(kin-attention-coords-list)</i> <i>(contact-target-coords-list)</i> <i>(contact-attention-coords-list)</i> <i>(variant-joint-angle-margin 3.0)</i> <i>(invariant-joint-angle-margin 3.0)</i> <i>(delta-linear-joint)</i> <i>(delta-rotational-joint)</i> <i>(contact-constraint-list (send-all contact-attention-coords-list :get :contact-constraint))</i> <i>(posture-joint-list)</i> <i>(posture-joint-angle-list)</i> <i>(external-wrench-list)</i> <i>(external-coords-list)</i> <i>(collision-pair-list)</i> <i>(collision-distance-margin 0.01)</i> <i>(collision-distance-margin-list)</i> <i>(kin-scale 1.0)</i> <i>(kin-scale-list)</i> <i>(kin-scale-mat-list)</i> <i>(target-posture-scale 0.001)</i> <i>(norm-regular-scale-max (if only-kinematics? 0.001 1.000000e-05))</i> <i>(norm-regular-scale-offset 1.000000e-07)</i> <i>(torque-regular-scale 1.000000e-04)</i> <i>ℰallow-other-keys</i>	[method]
	Initialize instance	
:robot-env	return robot-environment instance	[method]
:variant-joint-list	return \mathcal{J}_{var}	[method]
:invariant-joint-list	return \mathcal{J}_{invar}	[method]
:drive-joint-list	return \mathcal{J}_{drive}	[method]
:only-kinematics?	return whether to consider only kinematics or not	[method]

:theta	[method]
return $\boldsymbol{\theta}$	
:wrench	[method]
return $\hat{\boldsymbol{w}}$	
:torque	[method]
return $\boldsymbol{\tau}$	
:phi	[method]
return $\boldsymbol{\phi}$	
:num-kin	[method]
return $N_{kin} := \mathcal{T}^{kin-trg} = \mathcal{T}^{kin-att} $	
:num-contact	[method]
return $N_{cnt} := \mathcal{T}^{cnt-trg} = \mathcal{T}^{cnt-att} $	
:num-variant-joint	[method]
return $N_{var-joint} := \mathcal{J}_{var} $	
:num-invariant-joint	[method]
return $N_{invar-joint} := \mathcal{J}_{invar} $	
:num-drive-joint	[method]
return $N_{drive-joint} := \mathcal{J}_{drive} $	
:num-posture-joint	[method]
return $N_{target-joint} := \mathcal{J}_{target} $	
:num-external	[method]
return $N_{ex} :=$ number of external wrench	
:num-collision	[method]
return $N_{col} :=$ number of collision check pairs	
:dim-variant-config	[method]
	$dim(\boldsymbol{q}_{var}) \quad := \quad dim(\boldsymbol{\theta}) + dim(\hat{\boldsymbol{w}}) + dim(\boldsymbol{\tau}) \quad (2.5)$
	$= \quad N_{var-joint} + 6N_{cnt} + N_{drive-joint} \quad (2.6)$
return $dim(\boldsymbol{q}_{var})$	
:dim-invariant-config	[method]
return $dim(\boldsymbol{q}_{invar}) := dim(\boldsymbol{\phi}) = N_{invar-joint}$	
:dim-config	[method]
return $dim(\boldsymbol{q}) := dim(\boldsymbol{q}_{var}) + dim(\boldsymbol{q}_{invar})$	
:dim-task	[method]

$$dim(\boldsymbol{e}) \quad := \quad dim(\boldsymbol{e}^{kin}) + dim(\boldsymbol{e}^{com-trans}) + dim(\boldsymbol{e}^{com-rot}) + dim(\boldsymbol{e}^{trq}) + dim(\boldsymbol{e}^{posture}) \quad (2.7)$$

$$= \quad 6N_{kin} + 3 + 3 + N_{drive-joint} + N_{posture-joint} \quad (2.8)$$

return $\dim(\mathbf{e})$

:variant-config-vector

[method]

return $\mathbf{q}_{var} := \begin{pmatrix} \boldsymbol{\theta} \\ \hat{\mathbf{w}} \\ \boldsymbol{\tau} \end{pmatrix}$

:invariant-config-vector

[method]

return $\mathbf{q}_{invar} := \boldsymbol{\phi}$

:config-vector

[method]

return $\mathbf{q} := \begin{pmatrix} \mathbf{q}_{var} \\ \mathbf{q}_{invar} \end{pmatrix} = \begin{pmatrix} \boldsymbol{\theta} \\ \hat{\mathbf{w}} \\ \boldsymbol{\tau} \\ \boldsymbol{\phi} \end{pmatrix}$

:set-theta *theta-new* *ℰkey* (*relative?* *nil*)

[method]

(*apply-to-robot?* *t*)

Set $\boldsymbol{\theta}$.

:set-wrench *wrench-new* *ℰkey* (*relative?* *nil*)

[method]

Set $\hat{\mathbf{w}}$.

:set-torque *torque-new* *ℰkey* (*relative?* *nil*)

[method]

Set $\boldsymbol{\tau}$.

:set-phi *phi-new* *ℰkey* (*relative?* *nil*)

[method]

(*apply-to-robot?* *t*)

Set $\boldsymbol{\phi}$.

:set-variant-config *variant-config-new* *ℰkey* (*relative?* *nil*)

[method]

(*apply-to-robot?* *t*)

Set \mathbf{q}_{var} .

:set-invariant-config *invariant-config-new* *ℰkey* (*relative?* *nil*)

[method]

(*apply-to-robot?* *t*)

Set \mathbf{q}_{invar} .

:set-config *config-new* *ℰkey* (*relative?* *nil*)

[method]

(*apply-to-robot?* *t*)

Set \mathbf{q} .

:kin-target-coords-list

[method]

$$T_m^{kin-trg} = \{\mathbf{p}_m^{kin-trg}, \mathbf{R}_m^{kin-trg}\} \quad (m = 1, 2, \dots, N_{kin}) \quad (2.9)$$

return $\mathcal{T}^{kin-trg} := \{T_1^{kin-trg}, T_2^{kin-trg}, \dots, T_{N_{kin}}^{kin-trg}\}$

:kin-attention-coords-list

[method]

$$T_m^{kin-att} = \{\mathbf{p}_m^{kin-att}, \mathbf{R}_m^{kin-att}\} \quad (m = 1, 2, \dots, N_{kin}) \quad (2.10)$$

return $\mathcal{T}^{kin-att} := \{T_1^{kin-att}, T_2^{kin-att}, \dots, T_{N_{kin}}^{kin-att}\}$

:contact-target-coords-list

[method]

$$T_m^{cnt-trg} = \{\mathbf{p}_m^{cnt-trg}, \mathbf{R}_m^{cnt-trg}\} \quad (m = 1, 2, \dots, N_{cnt}) \quad (2.11)$$

return $\mathcal{T}^{cnt-trg} := \{T_1^{cnt-trg}, T_2^{cnt-trg}, \dots, T_{N_{cnt}}^{cnt-trg}\}$

:contact-attention-coords-list

[method]

$$T_m^{cnt-att} = \{\mathbf{p}_m^{cnt-att}, \mathbf{R}_m^{cnt-att}\} \quad (m = 1, 2, \dots, N_{cnt}) \quad (2.12)$$

return $\mathcal{T}^{cnt-att} := \{T_1^{cnt-att}, T_2^{cnt-att}, \dots, T_{N_{cnt}}^{cnt-att}\}$

:contact-constraint-list

[method]

return list of contact-constraint instance

:wrench-list

[method]

return $\{\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_{N_{cnt}}\}$

:force-list

[method]

return $\{\mathbf{f}_1, \mathbf{f}_2, \dots, \mathbf{f}_{N_{cnt}}\}$

:moment-list

[method]

return $\{\mathbf{n}_1, \mathbf{n}_2, \dots, \mathbf{n}_{N_{cnt}}\}$

:external-wrench-list

[method]

return $\{\mathbf{w}_1^{ex}, \mathbf{w}_2^{ex}, \dots, \mathbf{w}_{N_{ex}}^{ex}\}$

:external-force-list

[method]

return $\{\mathbf{f}_1^{ex}, \mathbf{f}_2^{ex}, \dots, \mathbf{f}_{N_{ex}}^{ex}\}$

:external-moment-list

[method]

return $\{\mathbf{n}_1^{ex}, \mathbf{n}_2^{ex}, \dots, \mathbf{n}_{N_{ex}}^{ex}\}$

:mg-vec

[method]

return $m\mathbf{g}$

:cog \mathcal{E}_{key} (update? t)

[method]

return $\mathbf{p}_G(\mathbf{q})$

:kinematics-task-value \mathcal{E}_{key} (update? t)

[method]

$$\mathbf{e}^{kin}(\mathbf{q}) = \mathbf{e}^{kin}(\boldsymbol{\theta}, \phi) \quad (2.13)$$

$$= \begin{pmatrix} \mathbf{e}_1^{kin}(\boldsymbol{\theta}, \phi) \\ \mathbf{e}_2^{kin}(\boldsymbol{\theta}, \phi) \\ \vdots \\ \mathbf{e}_{N_{kin}}^{kin}(\boldsymbol{\theta}, \phi) \end{pmatrix} \quad (2.14)$$

$$\mathbf{e}_m^{kin}(\boldsymbol{\theta}, \phi) = K_{kin} \begin{pmatrix} \mathbf{p}_m^{kin-trg}(\boldsymbol{\theta}, \phi) - \mathbf{p}_m^{kin-att}(\boldsymbol{\theta}, \phi) \\ \mathbf{a} \left(\mathbf{R}_m^{kin-trg}(\boldsymbol{\theta}, \phi) \mathbf{R}_m^{kin-att}(\boldsymbol{\theta}, \phi)^T \right) \end{pmatrix} \in \mathbb{R}^6 \quad (m = 1, 2, \dots, N_{kin}) \quad (2.15)$$

$a(R)$ は姿勢行列 R の等価角軸ベクトルを表す .

return $e^{kin}(q) \in \mathbb{R}^{6N_{kin}}$

:eom-trans-task-value $\mathcal{E}key$ (update? t)

[method]

$$e^{eom-trans}(q) = e^{eom-trans}(\hat{w}) \quad (2.16)$$

$$= \sum_{m=1}^{N_{cnt}} f_m - mg + \sum_{m=1}^{N_{ex}} f_m^{ex} \quad (2.17)$$

return $e^{eom-trans}(q) \in \mathbb{R}^3$

:eom-rot-task-value $\mathcal{E}key$ (update? t)

[method]

$$e^{eom-rot}(q) = e^{eom-rot}(\theta, \hat{w}, \phi) \quad (2.18)$$

$$= \sum_{m=1}^{N_{cnt}} \{ (p_m^{cnt-trg}(\theta, \phi) - p_G(\theta, \phi)) \times f_m + n_m \} \\ + \sum_{m=1}^{N_{ex}} \{ (p_m^{ex}(\theta, \phi) - p_G(\theta, \phi)) \times f_m^{ex} + n_m^{ex} \} \quad (2.19)$$

return $e^{eom-rot}(q) \in \mathbb{R}^3$

:torque-task-value $\mathcal{E}key$ (update? t)

[method]

$$e^{trq}(q) = e^{trq}(\theta, \hat{w}, \tau, \phi) \quad (2.20)$$

$$= \tau + \sum_{m=1}^{N_{cnt}} \tau_m^{cnt}(\theta, \phi) - \tau^{grav}(\theta, \phi) + \sum_{m=1}^{N_{ex}} \tau_m^{ex}(\theta, \phi) \quad (2.21)$$

$$= \tau + \sum_{m=1}^{N_{cnt}} J_{drive-joint,m}^{cnt-trg}(\theta, \phi)^T w_m - \tau^{grav}(\theta, \phi) + \sum_{m=1}^{N_{ex}} J_{drive-joint,m}^{ex}(\theta, \phi)^T w_m^{ex} \quad (2.22)$$

$\tau_m^{cnt}(\theta, \phi)$ は m 番目の接触部位にかかる接触レンチ w_m による関節トルク , $\tau_m^{grav}(\theta, \phi)$ は自重による関節トルクを表す .

return $e^{trq}(q) \in \mathbb{R}^{N_{drive-joint}}$

:posture-task-value $\mathcal{E}key$ (update? t)

[method]

$$e^{posture}(q) = e^{posture}(\theta) \quad (2.23)$$

$$= k_{posture}(\bar{\theta}^{trg} - \bar{\theta}) \quad (2.24)$$

$\bar{\theta}^{trg}, \bar{\theta}$ は着目関節リスト $\mathcal{J}_{posture}$ の目標関節角と現在の関節角 .

return $e^{posture}(q) \in \mathbb{R}^{N_{posture-joint}}$

:task-value $\mathcal{E}key$ (update? t)

[method]

$$\text{return } e(q) := \begin{pmatrix} e^{kin}(q) \\ e^{eom-trans}(q) \\ e^{eom-rot}(q) \\ e^{trq}(q) \\ e^{posture}(q) \end{pmatrix} = \begin{pmatrix} e^{kin}(\theta, \phi) \\ e^{eom-trans}(\hat{w}) \\ e^{eom-rot}(\theta, \hat{w}, \phi) \\ e^{trq}(\theta, \hat{w}, \tau, \phi) \\ e^{posture}(\theta) \end{pmatrix}$$

:kinematics-task-jacobian-with-theta

[method]

$$\frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\theta}} = \begin{pmatrix} \frac{\partial \mathbf{e}_1^{kin}}{\partial \boldsymbol{\theta}} \\ \frac{\partial \mathbf{e}_2^{kin}}{\partial \boldsymbol{\theta}} \\ \vdots \\ \frac{\partial \mathbf{e}_{N_{kin}}^{kin}}{\partial \boldsymbol{\theta}} \end{pmatrix} \quad (2.25)$$

$$\frac{\partial \mathbf{e}_m^{kin}}{\partial \boldsymbol{\theta}} = K_{kin} \left\{ \mathbf{J}_{\theta,m}^{kin-trg}(\boldsymbol{\theta}, \phi) - \mathbf{J}_{\theta,m}^{kin-att}(\boldsymbol{\theta}, \phi) \right\} \quad (m = 1, 2, \dots, N_{kin}) \quad (2.26)$$

$$\text{return } \frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\theta}} \in \mathbb{R}^{6N_{kin} \times N_{var-joint}}$$

:kinematics-task-jacobian-with-phi

[method]

$$\frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\phi}} = \begin{pmatrix} \frac{\partial \mathbf{e}_1^{kin}}{\partial \boldsymbol{\phi}} \\ \frac{\partial \mathbf{e}_2^{kin}}{\partial \boldsymbol{\phi}} \\ \vdots \\ \frac{\partial \mathbf{e}_{N_{kin}}^{kin}}{\partial \boldsymbol{\phi}} \end{pmatrix} \quad (2.27)$$

$$\frac{\partial \mathbf{e}_m^{kin}}{\partial \boldsymbol{\phi}} = K_{kin} \left\{ \mathbf{J}_{\phi,m}^{kin-trg}(\boldsymbol{\theta}, \phi) - \mathbf{J}_{\phi,m}^{kin-att}(\boldsymbol{\theta}, \phi) \right\} \quad (m = 1, 2, \dots, N_{kin}) \quad (2.28)$$

$$\text{return } \frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\phi}} \in \mathbb{R}^{6N_{kin} \times N_{invar-joint}}$$

:eom-trans-task-jacobian-with-wrench

[method]

$$\frac{\partial \mathbf{e}^{eom-trans}}{\partial \hat{\mathbf{w}}} = \begin{pmatrix} \frac{\partial \mathbf{e}^{eom-trans}}{\partial \mathbf{f}_1} & \frac{\partial \mathbf{e}^{eom-trans}}{\partial \mathbf{n}_1} & \dots & \frac{\partial \mathbf{e}^{eom-trans}}{\partial \mathbf{f}_{N_{cnt}}} & \frac{\partial \mathbf{e}^{eom-trans}}{\partial \mathbf{n}_{N_{cnt}}} \end{pmatrix} \quad (2.29)$$

$$= \begin{pmatrix} \mathbf{I}_3 & \mathbf{O}_3 & \dots & \mathbf{I}_3 & \mathbf{O}_3 \end{pmatrix} \quad (2.30)$$

$$\text{return } \frac{\partial \mathbf{e}^{eom-trans}}{\partial \hat{\mathbf{w}}} \in \mathbb{R}^{3 \times 6N_{cnt}}$$

:eom-rot-task-jacobian-with-theta

[method]

$$\begin{aligned} \frac{\partial \mathbf{e}^{eom-rot}}{\partial \boldsymbol{\theta}} &= \sum_{m=1}^{N_{cnt}} \left\{ -[\mathbf{f}_m \times] \left(\mathbf{J}_{\theta,m}^{cnt-trg}(\boldsymbol{\theta}, \phi) - \mathbf{J}_{G\theta}(\boldsymbol{\theta}, \phi) \right) \right\} \\ &\quad + \sum_{m=1}^{N_{ex}} \left\{ -[\mathbf{f}_m^{ex} \times] \left(\mathbf{J}_{\theta,m}^{ex}(\boldsymbol{\theta}, \phi) - \mathbf{J}_{G\theta}(\boldsymbol{\theta}, \phi) \right) \right\} \end{aligned} \quad (2.31)$$

$$\begin{aligned} &= \left[\left(\sum_{m=1}^{N_{cnt}} \mathbf{f}_m + \sum_{m=1}^{N_{ex}} \mathbf{f}_m^{ex} \right) \times \right] \mathbf{J}_{G\theta}(\boldsymbol{\theta}, \phi) \\ &\quad - \sum_{m=1}^{N_{cnt}} [\mathbf{f}_m \times] \mathbf{J}_{\theta,m}^{cnt-trg}(\boldsymbol{\theta}, \phi) - \sum_{m=1}^{N_{ex}} [\mathbf{f}_m^{ex} \times] \mathbf{J}_{\theta,m}^{ex}(\boldsymbol{\theta}, \phi) \end{aligned} \quad (2.32)$$

$\sum_{m=1}^{N_{cnt}} \mathbf{f}_m + \sum_{m=1}^{N_{ex}} \mathbf{f}_m^{ex} = m\mathbf{g}$ つまり, eom-trans-task が成立すると仮定すると次式が成り立つ.

$$\frac{\partial \mathbf{e}^{eom-rot}}{\partial \boldsymbol{\theta}} = [m\mathbf{g} \times] \mathbf{J}_{G\theta}(\boldsymbol{\theta}, \phi) - \sum_{m=1}^{N_{cnt}} [\mathbf{f}_m \times] \mathbf{J}_{\theta,m}^{cnt-trg}(\boldsymbol{\theta}, \phi) - \sum_{m=1}^{N_{ex}} [\mathbf{f}_m^{ex} \times] \mathbf{J}_{\theta,m}^{ex}(\boldsymbol{\theta}, \phi) \quad (2.33)$$

return $\frac{\partial \mathbf{e}^{eom-rot}}{\partial \boldsymbol{\theta}} \in \mathbb{R}^{3 \times N_{var-joint}}$

:eom-rot-task-jacobian-with-wrench

[method]

$$\frac{\partial \mathbf{e}^{eom-rot}}{\partial \hat{\mathbf{w}}} = \begin{pmatrix} \frac{\partial \mathbf{e}^{eom-rot}}{\partial \mathbf{f}_1} & \frac{\partial \mathbf{e}^{eom-rot}}{\partial \mathbf{n}_1} & \cdots & \frac{\partial \mathbf{e}^{eom-rot}}{\partial \mathbf{f}_{N_{cnt}}} & \frac{\partial \mathbf{e}^{eom-rot}}{\partial \mathbf{n}_{N_{cnt}}} \end{pmatrix} \quad (2.34)$$

$$\frac{\partial \mathbf{e}^{eom-rot}}{\partial \mathbf{f}_m} = [(\mathbf{p}_m^{cnt-trg}(\boldsymbol{\theta}, \phi) - \mathbf{p}_G(\boldsymbol{\theta}, \phi)) \times] \quad (m = 1, 2, \dots, N_{cnt}) \quad (2.35)$$

$$\frac{\partial \mathbf{e}^{eom-rot}}{\partial \mathbf{n}_m} = \mathbf{I}_3 \quad (m = 1, 2, \dots, N_{cnt}) \quad (2.36)$$

return $\frac{\partial \mathbf{e}^{eom-rot}}{\partial \hat{\mathbf{w}}} \in \mathbb{R}^{3 \times 6N_{cnt}}$

:eom-rot-task-jacobian-with-phi

[method]

$$\begin{aligned} \frac{\partial \mathbf{e}^{eom-rot}}{\partial \phi} &= \sum_{m=1}^{N_{cnt}} \left\{ -[\mathbf{f}_m \times] \left(\mathbf{J}_{\phi, m}^{cnt-trg}(\boldsymbol{\theta}, \phi) - \mathbf{J}_{G\phi}(\boldsymbol{\theta}, \phi) \right) \right\} \\ &\quad + \sum_{m=1}^{N_{ex}} \left\{ -[\mathbf{f}_m^{ex} \times] \left(\mathbf{J}_{\phi, m}^{ex}(\boldsymbol{\theta}, \phi) - \mathbf{J}_{G\phi}(\boldsymbol{\theta}, \phi) \right) \right\} \end{aligned} \quad (2.37)$$

$$\begin{aligned} &= \left[\left(\sum_{m=1}^{N_{cnt}} \mathbf{f}_m + \sum_{m=1}^{N_{ex}} \mathbf{f}_m^{ex} \right) \times \right] \mathbf{J}_{G\phi}(\boldsymbol{\theta}, \phi) \\ &\quad - \sum_{m=1}^{N_{cnt}} [\mathbf{f}_m \times] \mathbf{J}_{\phi, m}^{cnt-trg}(\boldsymbol{\theta}, \phi) - \sum_{m=1}^{N_{ex}} [\mathbf{f}_m^{ex} \times] \mathbf{J}_{\phi, m}^{ex}(\boldsymbol{\theta}, \phi) \end{aligned} \quad (2.38)$$

$\sum_{m=1}^{N_{cnt}} \mathbf{f}_m + \sum_{m=1}^{N_{ex}} \mathbf{f}_m^{ex} = m\mathbf{g}$ つまり, eom-trans-task が成立すると仮定すると次式が成り立つ.

$$\frac{\partial \mathbf{e}^{eom-rot}}{\partial \phi} = [m\mathbf{g} \times] \mathbf{J}_{G\phi}(\boldsymbol{\theta}, \phi) - \sum_{m=1}^{N_{cnt}} [\mathbf{f}_m \times] \mathbf{J}_{\phi, m}^{cnt-trg}(\boldsymbol{\theta}, \phi) - \sum_{m=1}^{N_{ex}} [\mathbf{f}_m^{ex} \times] \mathbf{J}_{\phi, m}^{ex}(\boldsymbol{\theta}, \phi) \quad (2.39)$$

return $\frac{\partial \mathbf{e}^{eom-rot}}{\partial \phi} \in \mathbb{R}^{3 \times N_{invar-joint}}$

:torque-task-jacobian-with-theta

[method]

$$\frac{\partial \mathbf{e}^{trq}}{\partial \boldsymbol{\theta}} = \sum_{m=1}^{N_{cnt}} \frac{\partial \boldsymbol{\tau}_m^{cnt}}{\partial \boldsymbol{\theta}} - \frac{\partial \boldsymbol{\tau}^{grav}}{\partial \boldsymbol{\theta}} + \sum_{m=1}^{N_{ex}} \frac{\partial \boldsymbol{\tau}_m^{ex}}{\partial \boldsymbol{\theta}} \quad (2.40)$$

return $\frac{\partial \mathbf{e}^{trq}}{\partial \boldsymbol{\theta}} \in \mathbb{R}^{N_{drive-joint} \times N_{var-joint}}$

:torque-task-jacobian-with-wrench

[method]

$$\frac{\partial \mathbf{e}^{trq}}{\partial \hat{\mathbf{w}}} = \begin{pmatrix} \frac{\partial \mathbf{e}^{trq}}{\partial \mathbf{w}_1} & \frac{\partial \mathbf{e}^{trq}}{\partial \mathbf{w}_2} & \cdots & \frac{\partial \mathbf{e}^{trq}}{\partial \mathbf{w}_{N_{cnt}}} \end{pmatrix} \quad (2.41)$$

$$\frac{\partial \mathbf{e}^{trq}}{\partial \mathbf{w}_m} = \mathbf{J}_{drive-joint, m}^{cnt-trq}(\boldsymbol{\theta}, \phi)^T \quad (m = 1, 2, \dots, N_{cnt}) \quad (2.42)$$

return $\frac{\partial \mathbf{e}^{trq}}{\partial \hat{\mathbf{w}}} \in \mathbb{R}^{N_{drive-joint} \times 6N_{cnt}}$

:torque-task-jacobian-with-phi

[method]

$$\frac{\partial \mathbf{e}^{trq}}{\partial \phi} = \sum_{m=1}^{N_{cnt}} \frac{\partial \tau_m^{cnt}}{\partial \phi} - \frac{\partial \tau_m^{grav}}{\partial \phi} + \sum_{m=1}^{N_{ex}} \frac{\partial \tau_m^{ex}}{\partial \phi} \quad (2.43)$$

$$\text{return } \frac{\partial \mathbf{e}^{trq}}{\partial \phi} \in \mathbb{R}^{N_{drive-joint} \times N_{invar-joint}}$$

:torque-task-jacobian-with-torque

[method]

$$\frac{\partial \mathbf{e}^{trq}}{\partial \tau} = \mathbf{I}_{N_{drive-joint}} \quad (2.44)$$

$$\text{return } \frac{\partial \mathbf{e}^{trq}}{\partial \tau} \in \mathbb{R}^{N_{drive-joint} \times N_{drive-joint}}$$

:posture-task-jacobian-with-theta *key (update? nil)*

[method]

$$\left(\frac{\partial \mathbf{e}^{posture}}{\partial \theta} \right)_{i,j} = \begin{cases} -k_{posture} & (\mathcal{J}_{posture,i} = \mathcal{J}_{var,j}) \\ 0 & \text{otherwise} \end{cases} \quad (2.45)$$

$$\text{return } \frac{\partial \mathbf{e}^{posture}}{\partial \theta} \in \mathbb{R}^{N_{posture-joint} \times N_{var-joint}}$$

:variant-task-jacobian

[method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{var}} = \begin{matrix} 6N_{kin} \\ 3 \\ 3 \\ N_{drive-joint} \\ N_{posture-joint} \end{matrix} \begin{pmatrix} N_{var-joint} & 6N_{cnt} & N_{drive-joint} \\ \frac{\partial \mathbf{e}^{kin}}{\partial \theta} & \frac{\partial \mathbf{e}^{com-trans}}{\partial \hat{\mathbf{w}}} & \\ \frac{\partial \mathbf{e}^{com-rot}}{\partial \theta} & \frac{\partial \mathbf{e}^{com-rot}}{\partial \hat{\mathbf{w}}} & \\ \frac{\partial \mathbf{e}^{trq}}{\partial \theta} & \frac{\partial \mathbf{e}^{trq}}{\partial \hat{\mathbf{w}}} & \frac{\partial \mathbf{e}^{trq}}{\partial \tau} \\ \frac{\partial \mathbf{e}^{posture}}{\partial \theta} & & \end{pmatrix} \quad (2.46)$$

$$\text{return } \frac{\partial \mathbf{e}}{\partial \mathbf{q}_{var}} \in \mathbb{R}^{(6N_{kin}+3+3+N_{drive-joint}+N_{posture-joint}) \times (N_{var-joint}+6N_{cnt}+N_{drive-joint})}$$

:invariant-task-jacobian

[method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{invar}} = \begin{matrix} 6N_{kin} \\ 3 \\ 3 \\ N_{drive-joint} \\ N_{posture-joint} \end{matrix} \begin{pmatrix} N_{invar-joint} \\ \frac{\partial \mathbf{e}^{kin}}{\partial \phi} \\ \frac{\partial \mathbf{e}^{com-rot}}{\partial \phi} \\ \frac{\partial \mathbf{e}^{trq}}{\partial \phi} \\ \end{pmatrix} \quad (2.47)$$

$$\text{return } \frac{\partial \mathbf{e}}{\partial \mathbf{q}_{invar}} \in \mathbb{R}^{(6N_{kin}+3+3+N_{drive-joint}+N_{posture-joint}) \times N_{invar-joint}}$$

:task-jacobian

[method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}} = \begin{pmatrix} \frac{\partial \mathbf{e}}{\partial \mathbf{q}_{var}} & \frac{\partial \mathbf{e}}{\partial \mathbf{q}_{invar}} \end{pmatrix} \quad (2.48)$$

$$= \begin{matrix} & N_{var-joint} & 6N_{cnt} & N_{drive-joint} & N_{invar-joint} \\ 6N_{kin} & \left(\frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\theta}} & & & \frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\phi}} \right) \\ 3 & & \frac{\partial \mathbf{e}^{com-trans}}{\partial \hat{\mathbf{w}}} & & \\ 3 & \frac{\partial \mathbf{e}^{com-rot}}{\partial \boldsymbol{\theta}} & \frac{\partial \mathbf{e}^{com-rot}}{\partial \hat{\mathbf{w}}} & & \frac{\partial \mathbf{e}^{com-rot}}{\partial \boldsymbol{\phi}} \\ N_{drive-joint} & \frac{\partial \mathbf{e}^{trq}}{\partial \boldsymbol{\theta}} & \frac{\partial \mathbf{e}^{trq}}{\partial \hat{\mathbf{w}}} & \frac{\partial \mathbf{e}^{trq}}{\partial \boldsymbol{\tau}} & \frac{\partial \mathbf{e}^{trq}}{\partial \boldsymbol{\phi}} \\ N_{posture-joint} & \frac{\partial \mathbf{e}^{posture}}{\partial \boldsymbol{\theta}} & & & \end{matrix} \quad (2.49)$$

return $\frac{\partial \mathbf{e}}{\partial \mathbf{q}} \in \mathbb{R}^{(6N_{kin}+3+3+N_{drive-joint}+N_{posture-joint}) \times (N_{var-joint}+6N_{cnt}+N_{drive-joint}+N_{invar-joint})}$

:theta-max-vector $\mathcal{E}key$ (update? nil) [method]

return $\boldsymbol{\theta}_{max} \in \mathbb{R}^{N_{var-joint}}$

:theta-min-vector $\mathcal{E}key$ (update? nil) [method]

return $\boldsymbol{\theta}_{min} \in \mathbb{R}^{N_{var-joint}}$

:delta-theta-limit-vector $\mathcal{E}key$ (update? nil) [method]

get trust region of $\boldsymbol{\theta}$

return $\Delta \boldsymbol{\theta}_{limit}$

:theta-inequality-constraint-matrix $\mathcal{E}key$ (update? nil) [method]

$$\begin{cases} \boldsymbol{\theta}_{min} \leq \boldsymbol{\theta} + \Delta \boldsymbol{\theta} \leq \boldsymbol{\theta}_{max} \\ -\Delta \boldsymbol{\theta}_{limit} \leq \Delta \boldsymbol{\theta} \leq \Delta \boldsymbol{\theta}_{limit} \end{cases} \quad (\text{if } \Delta \boldsymbol{\theta}_{limit} \text{ is set}) \quad (2.50)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \\ \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \Delta \boldsymbol{\theta} \geq \begin{pmatrix} \boldsymbol{\theta}_{min} - \boldsymbol{\theta} \\ -(\boldsymbol{\theta}_{max} - \boldsymbol{\theta}) \\ -\Delta \boldsymbol{\theta}_{limit} \\ -\Delta \boldsymbol{\theta}_{limit} \end{pmatrix} \quad (2.51)$$

$$\Leftrightarrow \mathbf{C}_{\boldsymbol{\theta}} \Delta \boldsymbol{\theta} \geq \mathbf{d}_{\boldsymbol{\theta}} \quad (2.52)$$

$$\text{return } \mathbf{C}_{\boldsymbol{\theta}} := \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \\ \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \in \mathbb{R}^{4N_{var-joint} \times N_{var-joint}}$$

:theta-inequality-constraint-vector $\mathcal{E}key$ (update? t) [method]

$$\text{return } \mathbf{d}_{\boldsymbol{\theta}} := \begin{pmatrix} \boldsymbol{\theta}_{min} - \boldsymbol{\theta} \\ -(\boldsymbol{\theta}_{max} - \boldsymbol{\theta}) \\ -\Delta \boldsymbol{\theta}_{limit} \\ -\Delta \boldsymbol{\theta}_{limit} \end{pmatrix} \in \mathbb{R}^{4N_{var-joint}}$$

:wrench-inequality-constraint-matrix $\mathcal{E}key$ (update? t) [method]

接触レンチ $\mathbf{w} \in \mathbb{R}^6$ が満たすべき制約（非負制約，摩擦制約，圧力中心制約）が次式のように表されるとする．

$$\mathbf{C}_w \mathbf{w} \geq \mathbf{d}_w \quad (2.53)$$

N_{cnt} 箇所の接触部位の接触レンチを並べたベクトル \hat{w} の不等式制約は次式で表される .

$$C_{w,m}(\mathbf{w}_m + \Delta \mathbf{w}_m) \geq \mathbf{d}_{w,m} \quad (m = 1, 2, \dots, N_{cnt}) \quad (2.54)$$

$$\Leftrightarrow C_{w,m} \Delta \mathbf{w}_m \geq \mathbf{d}_{w,m} - C_{w,m} \mathbf{w}_m \quad (m = 1, 2, \dots, N_{cnt}) \quad (2.55)$$

$$\Leftrightarrow \begin{pmatrix} C_{w,1} & & & \\ & C_{w,2} & & \\ & & \ddots & \\ & & & C_{w,N_{cnt}} \end{pmatrix} \begin{pmatrix} \Delta \mathbf{w}_1 \\ \Delta \mathbf{w}_2 \\ \vdots \\ \Delta \mathbf{w}_{N_{cnt}} \end{pmatrix} \geq \begin{pmatrix} \mathbf{d}_{w,1} - C_{w,1} \mathbf{w}_1 \\ \mathbf{d}_{w,2} - C_{w,2} \mathbf{w}_2 \\ \vdots \\ \mathbf{d}_{w,N_{cnt}} - C_{w,N_{cnt}} \mathbf{w}_{N_{cnt}} \end{pmatrix} \quad (2.56)$$

$$\Leftrightarrow C_{\hat{w}} \Delta \hat{\mathbf{w}} \geq \mathbf{d}_{\hat{w}} \quad (2.57)$$

$$\text{return } C_{\hat{w}} := \begin{pmatrix} C_{w,1} & & & \\ & C_{w,2} & & \\ & & \ddots & \\ & & & C_{w,N_{cnt}} \end{pmatrix} \in \mathbb{R}^{N_{wrench-ineq} \times \dim(\hat{\mathbf{w}})}$$

:wrench-inequality-constraint-vector $\mathcal{E}key \text{ (update? } t)$ [method]

$$\text{return } \mathbf{d}_{\hat{w}} := \begin{pmatrix} \mathbf{d}_{w,1} - C_{w,1} \mathbf{w}_1 \\ \mathbf{d}_{w,2} - C_{w,2} \mathbf{w}_2 \\ \vdots \\ \mathbf{d}_{w,N_{cnt}} - C_{w,N_{cnt}} \mathbf{w}_{N_{cnt}} \end{pmatrix} \in \mathbb{R}^{N_{wrench-ineq}}$$

:torque-max-vector $\mathcal{E}key \text{ (update? nil)}$ [method]

$$\text{return } \boldsymbol{\tau}_{max} \in \mathbb{R}^{N_{drive-joint}}$$

:torque-min-vector $\mathcal{E}key \text{ (update? nil)}$ [method]

$$\text{return } \boldsymbol{\tau}_{min} \in \mathbb{R}^{N_{drive-joint}}$$

:torque-inequality-constraint-matrix $\mathcal{E}key \text{ (update? nil)}$ [method]

$$\boldsymbol{\tau}_{min} \leq \boldsymbol{\tau} + \Delta \boldsymbol{\tau} \leq \boldsymbol{\tau}_{max} \quad (2.58)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \Delta \boldsymbol{\tau} \geq \begin{pmatrix} \boldsymbol{\tau}_{min} - \boldsymbol{\tau} \\ -(\boldsymbol{\tau}_{max} - \boldsymbol{\tau}) \end{pmatrix} \quad (2.59)$$

$$\Leftrightarrow C_{\boldsymbol{\tau}} \Delta \boldsymbol{\tau} \geq \mathbf{d}_{\boldsymbol{\tau}} \quad (2.60)$$

$$\text{return } C_{\boldsymbol{\tau}} := \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \in \mathbb{R}^{2N_{drive-joint} \times N_{drive-joint}}$$

:torque-inequality-constraint-vector $\mathcal{E}key \text{ (update? } t)$ [method]

$$\text{return } \mathbf{d}_{\boldsymbol{\tau}} := \begin{pmatrix} \boldsymbol{\tau}_{min} - \boldsymbol{\tau} \\ -(\boldsymbol{\tau}_{max} - \boldsymbol{\tau}) \end{pmatrix} \in \mathbb{R}^{2N_{drive-joint}}$$

:phi-max-vector $\mathcal{E}key \text{ (update? nil)}$ [method]

$$\text{return } \boldsymbol{\phi}_{max} \in \mathbb{R}^{N_{invar-joint}}$$

:phi-min-vector $\mathcal{E}key \text{ (update? nil)}$ [method]

$$\text{return } \boldsymbol{\phi}_{min} \in \mathbb{R}^{N_{invar-joint}}$$

:delta-phi-limit-vector $\mathcal{E}key \text{ (update? nil)}$ [method]

get trust region of $\boldsymbol{\phi}$

$$\text{return } \Delta \boldsymbol{\phi}_{limit}$$

:phi-inequality-constraint-matrix $\mathcal{E}key$ (*update? nil*)

[method]

$$\begin{cases} \phi_{min} \leq \phi + \Delta\phi \leq \phi_{max} \\ -\Delta\phi_{limit} \leq \Delta\phi \leq \Delta\phi_{limit} \quad (\text{if } \Delta\phi_{limit} \text{ is set}) \end{cases} \quad (2.61)$$

$$\Leftrightarrow \begin{pmatrix} I \\ -I \\ I \\ -I \end{pmatrix} \Delta\phi \geq \begin{pmatrix} \phi_{min} - \phi \\ -(\phi_{max} - \phi) \\ -\Delta\phi_{limit} \\ -\Delta\phi_{limit} \end{pmatrix} \quad (2.62)$$

$$\Leftrightarrow C_\phi \Delta\phi \geq d_\phi \quad (2.63)$$

$$\text{return } C_\phi := \begin{pmatrix} I \\ -I \\ I \\ -I \end{pmatrix} \in \mathbb{R}^{4N_{invar-joint} \times N_{invar-joint}}$$

:phi-inequality-constraint-vector $\mathcal{E}key$ (*update? t*)

[method]

$$\text{return } d_\phi := \begin{pmatrix} \phi_{min} - \phi \\ -(\phi_{max} - \phi) \\ -\Delta\phi_{limit} \\ -\Delta\phi_{limit} \end{pmatrix} \in \mathbb{R}^{4N_{invar-joint}}$$

:variant-config-inequality-constraint-matrix $\mathcal{E}key$ (*update? nil*)

[method]

$$\begin{cases} C_\theta \Delta\theta \geq d_\theta \\ C_{\hat{w}} \Delta\hat{w} \geq d_{\hat{w}} \\ C_\tau \Delta\tau \geq d_\tau \end{cases} \quad (2.64)$$

$$\Leftrightarrow \begin{pmatrix} C_\theta & & \\ & C_{\hat{w}} & \\ & & C_\tau \end{pmatrix} \begin{pmatrix} \Delta\theta \\ \Delta\hat{w} \\ \Delta\tau \end{pmatrix} \geq \begin{pmatrix} d_\theta \\ d_{\hat{w}} \\ d_\tau \end{pmatrix} \quad (2.65)$$

$$\Leftrightarrow C_{var} \Delta q_{var} \geq d_{var} \quad (2.66)$$

$$\text{return } C_{var} := \begin{pmatrix} C_\theta & & \\ & C_{\hat{w}} & \\ & & C_\tau \end{pmatrix} \in \mathbb{R}^{N_{var-ineq} \times \dim(\mathbf{q}_{var})}$$

:variant-config-inequality-constraint-vector $\mathcal{E}key$ (*update? t*)

[method]

$$\text{return } d_{var} := \begin{pmatrix} d_\theta \\ d_{\hat{w}} \\ d_\tau \end{pmatrix} \in \mathbb{R}^{N_{var-ineq}}$$

:invariant-config-inequality-constraint-matrix $\mathcal{E}key$ (*update? nil*)

[method]

$$C_\phi \Delta\phi \geq d_\phi \quad (2.67)$$

$$\Leftrightarrow C_{invar} \Delta q_{invar} \geq d_{invar} \quad (2.68)$$

$$\text{return } C_{invar} := C_\phi \in \mathbb{R}^{N_{invar-ineq} \times \dim(\mathbf{q}_{invar})}$$

:invariant-config-inequality-constraint-vector $\mathcal{E}key$ (*update? t*)

[method]

$$\begin{cases} C_{var} \Delta \mathbf{q}_{var} \geq \mathbf{d}_{var} \\ C_{invar} \Delta \mathbf{q}_{invar} \geq \mathbf{d}_{invar} \\ C_{col} \begin{pmatrix} \Delta \mathbf{q}_{var} \\ \Delta \mathbf{q}_{invar} \end{pmatrix} \geq \mathbf{d}_{col} \end{cases} \quad (2.69)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{C}_{var} \\ \hline \mathbf{C}_{invar} \\ \mathbf{C}_{col} \end{pmatrix} \begin{pmatrix} \Delta \mathbf{q}_{var} \\ \Delta \mathbf{q}_{invar} \end{pmatrix} \geq \begin{pmatrix} \mathbf{d}_{var} \\ \mathbf{d}_{invar} \\ \mathbf{d}_{col} \end{pmatrix} \quad (2.70)$$

$$\Leftrightarrow C\Delta q \geq d \quad (2.71)$$

$$\text{return } C := \begin{pmatrix} C_{var} & \\ & C_{invar} \\ \hline & C_{col} \end{pmatrix} \in \mathbb{R}^{N_{ineq} \times \dim(\mathbf{q})}$$

$$\text{return } \mathbf{d} := \begin{pmatrix} \mathbf{d}_{var} \\ \mathbf{d}_{invar} \\ \mathbf{d}_{col} \end{pmatrix} \in \mathbb{R}^{N_{ineq}}$$

return $\mathbf{A}_{var} \in \mathbb{R}^{0 \times \dim(\mathbf{q}_{var})}$ (no equality constraint)

return $\mathbf{b}_{var} \in \mathbb{R}^0$ (no equality constraint)

return $\mathbf{A}_{invar} \in \mathbb{R}^{0 \times \dim(\mathbf{q}_{invar})}$ (no equality constraint)

return $\mathbf{b}_{invar} \in \mathbb{R}^0$ (no equality constraint)

return $\mathbf{A} \in \mathbb{R}^{0 \times \dim(\mathbf{q})}$ (no equality constraint)

return $\mathbf{b} \in \mathbb{R}^0$ (no equality constraint)

二次形式の正則化項として次式を考える.

$$F_{tau}(\mathbf{q}) = \left\| \frac{\boldsymbol{\tau}}{\tau_{max}} \right\|^2 \quad (\text{ベクトルの要素ごとの割り算を表す}) \quad (2.72)$$

$$= \tau^T \bar{W}_{tra} \tau \quad (2.73)$$

ここで,

$$\bar{\mathbf{W}}_{trq} := \begin{pmatrix} \frac{1}{\tau_{max,1}^2} & & & \\ & \frac{1}{\tau_{max,2}^2} & & \\ & & \ddots & \\ & & & \frac{1}{\tau_{max,N_{drive-joint}}^2} \end{pmatrix} \in \mathbb{R}^{dim(\boldsymbol{\tau}) \times dim(\boldsymbol{\tau})} \quad (2.74)$$

only-variant? is true:

$$\mathbf{W}_{trq} := \begin{matrix} & dim(\boldsymbol{\theta}) & dim(\hat{\mathbf{w}}) & dim(\boldsymbol{\tau}) \\ \begin{matrix} dim(\boldsymbol{\theta}) \\ dim(\hat{\mathbf{w}}) \\ dim(\boldsymbol{\tau}) \end{matrix} & \begin{pmatrix} & & \\ & & \\ & & \bar{\mathbf{W}}_{trq} \end{pmatrix} \end{matrix} \in \mathbb{R}^{dim(\mathbf{q}_{var}) \times dim(\mathbf{q}_{var})} \quad (2.75)$$

otherwise:

$$\mathbf{W}_{trq} := \begin{matrix} & dim(\boldsymbol{\theta}) & dim(\hat{\mathbf{w}}) & dim(\boldsymbol{\tau}) & dim(\boldsymbol{\phi}) \\ \begin{matrix} dim(\boldsymbol{\theta}) \\ dim(\hat{\mathbf{w}}) \\ dim(\boldsymbol{\tau}) \\ dim(\boldsymbol{\phi}) \end{matrix} & \begin{pmatrix} & & & \\ & & & \\ & & \bar{\mathbf{W}}_{trq} & \\ & & & \end{pmatrix} \end{matrix} \in \mathbb{R}^{dim(\mathbf{q}) \times dim(\mathbf{q})} \quad (2.76)$$

return \mathbf{W}_{trq}

:torque-regular-vector $\mathcal{E}key$ (*update? t*) [method]
(*only-variant? nil*)

$$\bar{\mathbf{v}}_{trq} := \bar{\mathbf{W}}_{trq} \boldsymbol{\tau} \quad (2.77)$$

$$= \begin{pmatrix} \frac{\tau_1}{\tau_{max,1}^2} \\ \frac{\tau_2}{\tau_{max,2}^2} \\ \vdots \\ \frac{\tau_{dim(\boldsymbol{\tau})}}{\tau_{max,dim(\boldsymbol{\tau})}^2} \end{pmatrix} \in \mathbb{R}^{dim(\boldsymbol{\tau})} \quad (2.78)$$

only-variant? is true:

$$\mathbf{v}_{trq} := \begin{matrix} & 1 \\ \begin{matrix} dim(\boldsymbol{\theta}) \\ dim(\hat{\mathbf{w}}) \\ dim(\boldsymbol{\tau}) \end{matrix} & \begin{pmatrix} \\ \\ \bar{\mathbf{v}}_{trq} \end{pmatrix} \end{matrix} \in \mathbb{R}^{dim(\mathbf{q}_{var})} \quad (2.79)$$

otherwise:

$$\mathbf{v}_{trq} := \begin{matrix} & 1 \\ \begin{matrix} dim(\boldsymbol{\theta}) \\ dim(\hat{\mathbf{w}}) \\ dim(\boldsymbol{\tau}) \\ dim(\boldsymbol{\phi}) \end{matrix} & \begin{pmatrix} \\ \\ \bar{\mathbf{v}}_{trq} \\ \end{pmatrix} \end{matrix} \in \mathbb{R}^{dim(\mathbf{q})} \quad (2.80)$$

return \mathbf{v}_{trq}

:torque-ratio

[method]

$$\text{return } \frac{\boldsymbol{\tau}}{\tau_{max}} := \begin{pmatrix} \frac{\tau_1}{\tau_{max,1}} \\ \frac{\tau_2}{\tau_{max,2}} \\ \vdots \\ \frac{\tau_{N_{drive-joint}}}{\tau_{max,N_{drive-joint}}} \end{pmatrix}$$

:regular-matrix

[method]

$$\mathbf{W}_{reg} := \min(k_{max}, \|\mathbf{e}\|^2 + k_{off})\mathbf{I} + k_{trq}\mathbf{W}_{trq} \quad (2.81)$$

$$\text{return } \mathbf{W}_{reg} \in \mathbb{R}^{dim(\mathbf{q}) \times dim(\mathbf{q})}$$

:regular-vector

[method]

$$\mathbf{v}_{reg} := k_{trq}\mathbf{v}_{trq} \quad (2.82)$$

$$\text{return } \mathbf{v}_{reg} \in \mathbb{R}^{dim(\mathbf{q})}$$

:update-collision-inequality-constraint

[method]

リンク 1 とリンク 2 の最近点を $\mathbf{p}_1, \mathbf{p}_2$ とする．リンク 1 とリンク 2 が干渉しない条件を，最近点 $\mathbf{p}_1, \mathbf{p}_2$ の距離が d_{margin} 以上である条件に置き換えて考える．これは次式で表される．

$$\mathbf{d}_{12}^T(\mathbf{p}_1 - \mathbf{p}_2) \geq d_{margin} \quad (2.83)$$

$$\text{where } \mathbf{d}_{12} = \mathbf{p}_1 - \mathbf{p}_2 \quad (2.84)$$

コンフィギュレーションが $\Delta \mathbf{q}$ だけ更新されてもこれが成立するための条件は次式で表される．

$$\mathbf{d}_{12}^T \{(\mathbf{p}_1 + \Delta \mathbf{p}_1) - (\mathbf{p}_2 + \Delta \mathbf{p}_2)\} \geq d_{margin} \quad (2.85)$$

$$\text{where } \Delta \mathbf{p}_1 = \mathbf{J}_{\theta,1}\Delta \boldsymbol{\theta} + \mathbf{J}_{\phi,1}\Delta \boldsymbol{\phi} \quad (2.86)$$

$$\Delta \mathbf{p}_2 = \mathbf{J}_{\theta,2}\Delta \boldsymbol{\theta} + \mathbf{J}_{\phi,2}\Delta \boldsymbol{\phi} \quad (2.87)$$

$$\mathbf{J}_{\theta,i} = \frac{\partial \mathbf{p}_i}{\partial \boldsymbol{\theta}}, \quad \mathbf{J}_{\phi,i} = \frac{\partial \mathbf{p}_i}{\partial \boldsymbol{\phi}} \quad (i = 1, 2) \quad (2.88)$$

これは以下のように変形される．

$$\mathbf{d}_{12}^T \{(\mathbf{p}_1 + \mathbf{J}_{\theta,1}\Delta \boldsymbol{\theta} + \mathbf{J}_{\phi,1}\Delta \boldsymbol{\phi}) - (\mathbf{p}_2 + \mathbf{J}_{\theta,2}\Delta \boldsymbol{\theta} + \mathbf{J}_{\phi,2}\Delta \boldsymbol{\phi})\} \geq d_{margin} \quad (2.89)$$

$$\Leftrightarrow \mathbf{d}_{12}^T(\mathbf{J}_{\theta,1} - \mathbf{J}_{\theta,2})\Delta \boldsymbol{\theta} + \mathbf{d}_{12}^T(\mathbf{J}_{\phi,1} - \mathbf{J}_{\phi,2})\Delta \boldsymbol{\phi} \geq -(\mathbf{d}_{12}^T(\mathbf{p}_1 - \mathbf{p}_2) - d_{margin}) \quad (2.90)$$

$$\Leftrightarrow \mathbf{c}_{col,var}^T \Delta \boldsymbol{\theta} + \mathbf{c}_{col,invar}^T \Delta \boldsymbol{\phi} \geq d_{col} \quad (2.91)$$

$$\text{where } \mathbf{c}_{col,var}^T = \mathbf{d}_{12}^T(\mathbf{J}_{\theta,1} - \mathbf{J}_{\theta,2}) \quad (2.92)$$

$$\mathbf{c}_{col,invar}^T = \mathbf{d}_{12}^T(\mathbf{J}_{\phi,1} - \mathbf{J}_{\phi,2}) \quad (2.93)$$

$$d_{col} = -(\mathbf{d}_{12}^T(\mathbf{p}_1 - \mathbf{p}_2) - d_{margin}) \quad (2.94)$$

i 番目の干渉回避リンクペアに関する行列，ベクトルをそれぞれ $\mathbf{c}_{col,var,i}^T, \mathbf{c}_{col,invar,i}^T, d_{col,i}$ とする． $i =$

$1, 2, \dots, N_{col}$ の全てのリンクペアにおいて干渉が生じないための条件は次式で表される .

$$\begin{pmatrix} \mathbf{C}_{col,\theta} & \mathbf{C}_{col,\phi} \end{pmatrix} \begin{pmatrix} \Delta\theta \\ \Delta\phi \end{pmatrix} \geq \mathbf{d}_{col} \quad (2.95)$$

$$\mathbf{C}_{col,\theta} := \begin{pmatrix} \mathbf{c}_{col,var,1}^T \\ \vdots \\ \mathbf{c}_{col,var,N_{col}}^T \end{pmatrix} \in \mathbb{R}^{N_{col} \times \dim(\theta)} \quad (2.96)$$

$$\mathbf{C}_{col,\phi} := \begin{pmatrix} \mathbf{c}_{col,invar,1}^T \\ \vdots \\ \mathbf{c}_{col,invar,N_{col}}^T \end{pmatrix} \in \mathbb{R}^{N_{col} \times \dim(\phi)}, \quad (2.97)$$

$$\mathbf{d}_{col} := \begin{pmatrix} d_{col,1} \\ \vdots \\ d_{col,N_{col}} \end{pmatrix} \in \mathbb{R}^{N_{col}} \quad (2.98)$$

update inequality matrix $\mathbf{C}_{col,\theta}, \mathbf{C}_{col,\phi}$ and inequality vector \mathbf{d}_{col} for collision avoidance

:collision-theta-inequality-constraint-matrix [method]

return $\mathbf{C}_{col,\theta} \in \mathbb{R}^{N_{col} \times \dim(\theta)}$

:collision-phi-inequality-constraint-matrix [method]

return $\mathbf{C}_{col,\phi} \in \mathbb{R}^{N_{col} \times \dim(\phi)}$

:collision-inequality-constraint-matrix *key (update? nil)* [method]

$$\mathbf{C}_{col} := N_{col} \begin{pmatrix} \dim(\theta) & \dim(\hat{\mathbf{w}}) & \dim(\tau) & \dim(\phi) \\ \mathbf{C}_{col,\theta} & \mathbf{O} & \mathbf{O} & \mathbf{C}_{col,\phi} \end{pmatrix} \quad (2.99)$$

return $\mathbf{C}_{col} \in \mathbb{R}^{N_{col} \times \dim(\mathbf{q})}$

:collision-inequality-constraint-vector *key (update? nil)* [method]

return $\mathbf{d}_{col} \in \mathbb{R}^{N_{col}}$

:update-viewer [method]

Update viewer.

:print-status [method]

Print status.

2.2 軌道コンフィギュレーションと軌道タスク関数

trajectory-configuration-task [class]

:super **propertied-object**

:slots (*_instant-config-task-list* list of instant-config-task instance)

(*_num-instant-config-task* L)

(*_dim-variant-config* $\dim(\mathbf{q}_{var})$)

(*_dim-invariant-config* $\dim(\mathbf{q}_{invar})$)

```

(dim-config  $\dim(\mathbf{q})$ )
(dim-task  $\dim(\mathbf{e})$ )
(norm-regular-scale-max  $k_{max}$ )
(norm-regular-scale-offset  $k_{off}$ )
(adjacent-regular-scale-list  $k_{adj}^{(1)}, k_{adj}^{(2)}, \dots, k_{adj}^{(L-1)}$ )
(torque-regular-scale  $k_{trq}$ )
(task-jacobi buffer for  $\frac{\partial \mathbf{e}}{\partial \mathbf{q}}$ )

```

軌道コンフィギュレーション \mathbf{q} と軌道タスク関数 $\mathbf{e}(\mathbf{q})$ のクラス .

以降では , 説明文やメソッド名で , “軌道” や “trajectory” を省略する .

コンフィギュレーション \mathbf{q} の取得・更新 , タスク関数 $\mathbf{e}(\mathbf{q})$ の取得 , タスク関数のヤコビ行列 $\frac{\partial \mathbf{e}(\mathbf{q})}{\partial \mathbf{q}}$ の取得 , コンフィギュレーションの等式・不等式制約 A, b, C, d の取得のためのメソッドが定義されている .

コンフィギュレーション・タスク関数を定めるために , 初期化時に以下を与える

- 瞬時のコンフィギュレーション・タスクのリスト

`instant-config-task-list` `instant-configuration-task` のリスト

- 目的関数の重み

`norm-regular-scale-max` k_{max} コンフィギュレーション更新量正則化の重み最大値

`norm-regular-scale-offset` k_{off} コンフィギュレーション更新量正則化の重みオフセット

`adjacent-regular-scale-list` $k_{adj}^{(l)}$ 隣接コンフィギュレーション正則化の重みのリスト

`torque-regular-scale` k_{trq} トルク正則化の重み

コンフィギュレーション \mathbf{q} は以下から構成される .

$$\mathbf{q} := \begin{pmatrix} \mathbf{q}_{var}^{(1)T} & \mathbf{q}_{var}^{(2)T} & \cdots & \mathbf{q}_{var}^{(L)T} & \mathbf{q}_{invar}^T \end{pmatrix}^T \quad (2.100)$$

ここで ,

$$\mathbf{q}_{invar} := \mathbf{q}_{invar}^{(1)} = \mathbf{q}_{invar}^{(2)} = \cdots = \mathbf{q}_{invar}^{(L)} \quad (2.101)$$

$\mathbf{q}_{var}^{(l)}, \mathbf{q}_{invar}^{(l)}$ ($l = 1, 2, \dots, L$) は l 番目の瞬時の時変 , 時不変コンフィギュレーションを表す .

タスク関数 $\mathbf{e}(\mathbf{q})$ は以下から構成される .

$$\mathbf{e}(\mathbf{q}) := \begin{pmatrix} \mathbf{e}^{(1)T}(\mathbf{q}_{var}^{(1)}, \mathbf{q}_{invar}^{(1)}) & \mathbf{e}^{(2)T}(\mathbf{q}_{var}^{(2)}, \mathbf{q}_{invar}^{(2)}) & \cdots & \mathbf{e}^{(L)T}(\mathbf{q}_{var}^{(L)}, \mathbf{q}_{invar}^{(L)}) \end{pmatrix}^T \quad (2.102)$$

$\mathbf{e}^{(l)}(\mathbf{q}_{var}^{(l)}, \mathbf{q}_{invar}^{(l)})$ ($l = 1, 2, \dots, L$) は l 番目の瞬時のタスク関数を表す .

:init *&key (name)* [method]

(instant-config-task-list)

(norm-regular-scale-max 1.000000e-04)

(norm-regular-scale-offset 1.000000e-07)

(adjacent-regular-scale 0.005)

(adjacent-regular-scale-list)

(torque-regular-scale 0.001)

Initialize instance

:instant-config-task-list [method]

return instant-config-task-list

:dim-variant-config [method]

return $\dim(\mathbf{q}_{var}) := \sum_{l=1}^L \dim(\mathbf{q}_{var}^{(l)})$

:dim-invariant-config [method]

return $\dim(\mathbf{q}_{invar}) := \dim(\mathbf{q}_{invar}^{(l)})$ ($l = 1, 2, \dots, L$ で同じ)

:dim-config [method]

return $\dim(\mathbf{q}) := \dim(\mathbf{q}_{var}) + \dim(\mathbf{q}_{invar})$

:dim-task [method]

return $\dim(\mathbf{e}) := \sum_{l=1}^L \dim(\mathbf{e}^{(l)})$

:variant-config-vector [method]

return $\mathbf{q}_{var} := \begin{pmatrix} \mathbf{q}_{var}^{(1)} \\ \mathbf{q}_{var}^{(2)} \\ \vdots \\ \mathbf{q}_{var}^{(L)} \end{pmatrix}$

:invariant-config-vector [method]

return $\mathbf{q}_{invar} := \mathbf{q}_{invar}^{(l)}$ ($l = 1, 2, \dots, L$ で同じ)

:config-vector [method]

return $\mathbf{q} := \begin{pmatrix} \mathbf{q}_{var} \\ \mathbf{q}_{invar} \end{pmatrix} = \begin{pmatrix} \mathbf{q}_{var}^{(1)} \\ \mathbf{q}_{var}^{(2)} \\ \vdots \\ \mathbf{q}_{var}^{(L)} \\ \mathbf{q}_{invar} \end{pmatrix}$

:set-variant-config *variant-config-new* *ℰkey* (*relative?* *nil*) [method]

(*apply-to-robot?* *t*)

Set \mathbf{q}_{var} .

:set-invariant-config *invariant-config-new* *ℰkey* (*relative?* *nil*) [method]

(*apply-to-robot?* *t*)

Set \mathbf{q}_{invar} .

:set-config *config-new* *ℰkey* (*relative?* *nil*) [method]

(*apply-to-robot?* *t*)

Set \mathbf{q} .

:task-value *ℰkey* (*update?* *t*) [method]

return $\mathbf{e}(\mathbf{q}) := \begin{pmatrix} \mathbf{e}^{(1)}(\mathbf{q}_{var}^{(1)}, \mathbf{q}_{invar}) \\ \mathbf{e}^{(2)}(\mathbf{q}_{var}^{(2)}, \mathbf{q}_{invar}) \\ \vdots \\ \mathbf{e}^{(L)}(\mathbf{q}_{var}^{(L)}, \mathbf{q}_{invar}) \end{pmatrix}$

:variant-task-jacobian [method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{var}} = \begin{pmatrix} \frac{\partial \mathbf{e}^{(1)}}{\partial \mathbf{q}_{var}^{(1)}} & & \mathbf{O} \\ & \frac{\partial \mathbf{e}^{(2)}}{\partial \mathbf{q}_{var}^{(2)}} & \\ & & \ddots \\ \mathbf{O} & & & \frac{\partial \mathbf{e}^{(L)}}{\partial \mathbf{q}_{var}^{(L)}} \end{pmatrix} \quad (2.103)$$

return $\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{var}} \in \mathbb{R}^{dim(\mathbf{e}) \times dim(\mathbf{q}_{var})}$

:invariant-task-jacobian

[method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{invar}} = \begin{pmatrix} \frac{\partial \mathbf{e}^{(1)}}{\partial \mathbf{q}_{invar}^{(1)}} \\ \frac{\partial \mathbf{e}^{(2)}}{\partial \mathbf{q}_{invar}^{(2)}} \\ \vdots \\ \frac{\partial \mathbf{e}^{(L)}}{\partial \mathbf{q}_{invar}^{(L)}} \end{pmatrix} \quad (2.104)$$

return $\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{invar}} \in \mathbb{R}^{dim(\mathbf{e}) \times dim(\mathbf{q}_{invar})}$

:task-jacobian

[method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}} = \begin{pmatrix} \frac{\partial \mathbf{e}}{\partial \mathbf{q}_{var}} & \frac{\partial \mathbf{e}}{\partial \mathbf{q}_{invar}} \end{pmatrix} \quad (2.105)$$

$$= \begin{pmatrix} \frac{\partial \mathbf{e}^{(1)}}{\partial \mathbf{q}_{var}^{(1)}} & & \mathbf{O} & \frac{\partial \mathbf{e}^{(1)}}{\partial \mathbf{q}_{invar}^{(1)}} \\ & \frac{\partial \mathbf{e}^{(2)}}{\partial \mathbf{q}_{var}^{(2)}} & & \frac{\partial \mathbf{e}^{(2)}}{\partial \mathbf{q}_{invar}^{(2)}} \\ & & \ddots & \\ \mathbf{O} & & & \frac{\partial \mathbf{e}^{(L)}}{\partial \mathbf{q}_{var}^{(L)}} & \frac{\partial \mathbf{e}^{(L)}}{\partial \mathbf{q}_{invar}^{(L)}} \end{pmatrix} \quad (2.106)$$

return $\frac{\partial \mathbf{e}}{\partial \mathbf{q}} \in \mathbb{R}^{dim(\mathbf{e}) \times dim(\mathbf{q})}$

:variant-config-inequality-constraint-matrix $\mathcal{E}key$ (*update? nil*)

[method]

$$\mathbf{C}_{var} := \begin{pmatrix} \mathbf{C}_{var}^{(1)} & & \mathbf{O} \\ & \mathbf{C}_{var}^{(2)} & \\ & & \ddots \\ \mathbf{O} & & & \mathbf{C}_{var}^{(L)} \end{pmatrix} \quad (2.107)$$

return $\mathbf{C}_{var} \in \mathbb{R}^{N_{var-ineq} \times dim(\mathbf{q}_{var})}$

:variant-config-inequality-constraint-vector $\mathcal{E}key$ (*update? t*)

[method]

$$\mathbf{d}_{var} := \begin{pmatrix} \mathbf{d}_{var}^{(1)} \\ \mathbf{d}_{var}^{(2)} \\ \vdots \\ \mathbf{d}_{var}^{(L)} \end{pmatrix} \quad (2.108)$$

return $\mathbf{d}_{var} \in \mathbb{R}^{N_{var-ineq}}$

:invariant-config-inequality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]

$$\mathbf{C}_{invar} := \mathbf{C}_{invar}^{(l)} \quad (l = 1, 2, \dots, L \text{ で同じ}) \quad (2.109)$$

return $\mathbf{C}_{invar} \in \mathbb{R}^{N_{invar-ineq} \times \dim(\mathbf{q}_{invar})}$

:invariant-config-inequality-constraint-vector $\mathcal{E}key$ (*update?* *t*) [method]

$$\mathbf{d}_{invar} := \mathbf{d}_{invar}^{(l)} \quad (l = 1, 2, \dots, L \text{ で同じ}) \quad (2.110)$$

return $\mathbf{d}_{invar} \in \mathbb{R}^{N_{invar-ineq}}$

:config-inequality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]
(*update-collision?* *nil*)

$$\mathbf{C} := \begin{pmatrix} \mathbf{C}_{var} & & \\ & \mathbf{C}_{invar} & \\ \hline & & \mathbf{C}_{col} \end{pmatrix} \in \mathbb{R}^{N_{ineq} \times \dim(\mathbf{q})} \quad (2.111)$$

return $\mathbf{C} \in \mathbb{R}^{N_{ineq} \times \dim(\mathbf{q})}$

:config-inequality-constraint-vector $\mathcal{E}key$ (*update?* *t*) [method]
(*update-collision?* *nil*)

$$\mathbf{d} := \begin{pmatrix} \mathbf{d}_{var} \\ \mathbf{d}_{invar} \\ \mathbf{d}_{col} \end{pmatrix} \quad (2.112)$$

return $\mathbf{d} \in \mathbb{R}^{N_{ineq}}$

:variant-config-equality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]

$$\mathbf{A}_{var} := \begin{pmatrix} \mathbf{A}_{var}^{(1)} & & & \mathbf{O} \\ & \mathbf{A}_{var}^{(2)} & & \\ & & \ddots & \\ \mathbf{O} & & & \mathbf{A}_{var}^{(L)} \end{pmatrix} \quad (2.113)$$

return $\mathbf{A}_{var} \in \mathbb{R}^{N_{var-eq} \times \dim(\mathbf{q}_{var})}$

:variant-config-equality-constraint-vector $\mathcal{E}key$ (*update?* *t*) [method]

$$\mathbf{b}_{var} := \begin{pmatrix} \mathbf{b}_{var}^{(1)} \\ \mathbf{b}_{var}^{(2)} \\ \vdots \\ \mathbf{b}_{var}^{(L)} \end{pmatrix} \quad (2.114)$$

return $\mathbf{b}_{var} \in \mathbb{R}^{N_{var-eq}}$

:invariant-config-equality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]

$$\mathbf{A}_{invar} := \mathbf{A}_{invar}^{(l)} \quad (l = 1, 2, \dots, L \text{ で同じ}) \quad (2.115)$$

return $\mathbf{A}_{invar} \in \mathbb{R}^{N_{invar-eq} \times \dim(\mathbf{q}_{invar})}$

:invariant-config-equality-constraint-vector $\mathcal{E}key$ (*update?* *t*) [method]

$$\mathbf{b}_{invar} := \mathbf{b}_{invar}^{(l)} \quad (l = 1, 2, \dots, L \text{ で同じ}) \quad (2.116)$$

return $\mathbf{b}_{invar} \in \mathbb{R}^{N_{invar-eq}}$

:config-equality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]

$$\mathbf{A} := \begin{pmatrix} \mathbf{A}_{var} & \\ & \mathbf{A}_{invar} \end{pmatrix} \in \mathbb{R}^{N_{eq} \times \dim(\mathbf{q})} \quad (2.117)$$

return $\mathbf{A} \in \mathbb{R}^{N_{eq} \times \dim(\mathbf{q})}$

:config-equality-constraint-vector $\mathcal{E}key$ (*update?* *t*) [method]

$$\mathbf{b} := \begin{pmatrix} \mathbf{b}_{var} \\ \mathbf{b}_{invar} \end{pmatrix} \quad (2.118)$$

return $\mathbf{b} \in \mathbb{R}^{N_{eq}}$

:update-collision-inequality-constraint [method]

update inequality matrix $\mathbf{C}_{col,\theta}^{(l)}, \mathbf{C}_{col,\phi}^{(l)}$ and inequality vector $\mathbf{d}_{col}^{(l)}$ for collision avoidance ($l = 1, 2, \dots, L$)

:collision-inequality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]

$$\hat{\mathbf{C}}_{col,\theta}^{(l)} := N_{col}^{(l)} \begin{pmatrix} \dim(\boldsymbol{\theta}^{(l)}) & \dim(\hat{\mathbf{w}}^{(l)}) & \dim(\boldsymbol{\tau}^{(l)}) \\ \mathbf{C}_{col,\theta}^{(l)} & \mathbf{O} & \mathbf{O} \end{pmatrix} \quad (2.119)$$

$$\mathbf{C}_{col} := \begin{pmatrix} \hat{\mathbf{C}}_{col,\theta}^{(1)} & & & \mathbf{C}_{col,\phi}^{(1)} \\ & \hat{\mathbf{C}}_{col,\theta}^{(2)} & & \mathbf{C}_{col,\phi}^{(2)} \\ & & \ddots & \vdots \\ & & & \hat{\mathbf{C}}_{col,\theta}^{(L)} & \mathbf{C}_{col,\phi}^{(L)} \end{pmatrix} \quad (2.120)$$

return $\mathbf{C}_{col} \in \mathbb{R}^{N_{col} \times \dim(\mathbf{q})}$

:collision-inequality-constraint-vector $\mathcal{E}key$ (*update?* *nil*) [method]

$$\mathbf{d}_{col} := \begin{pmatrix} \mathbf{d}_{col}^{(1)} \\ \mathbf{d}_{col}^{(2)} \\ \vdots \\ \mathbf{d}_{col}^{(L)} \end{pmatrix} \quad (2.121)$$

return $\mathbf{d}_{col} \in \mathbb{R}^{N_{col}}$

:adjacent-regular-matrix *ℰkey (update? nil)* [method]

二次形式の正則化項として次式を考える．

$$F_{adj}(\mathbf{q}) = \sum_{l=1}^{L-1} k_{adj}^{(l)} \|\boldsymbol{\theta}_{l+1} - \boldsymbol{\theta}_l\|^2 \quad (2.122)$$

$$= \mathbf{q}^T \mathbf{W}_{adj} \mathbf{q} \quad (2.123)$$

ここで，

$$\bar{\mathbf{I}}_{adj}^{(l)} := \begin{matrix} & \dim(\boldsymbol{\theta}^{(l)}) & \dim(\hat{\mathbf{w}}^{(l)}) & \dim(\boldsymbol{\tau}^{(l)}) \\ \dim(\boldsymbol{\theta}^{(l)}) & & & \\ \dim(\hat{\mathbf{w}}^{(l)}) & & & \\ \dim(\boldsymbol{\tau}^{(l)}) & & & \end{matrix} \begin{pmatrix} k_{adj}^{(l)} \mathbf{I} \\ \\ \\ \end{pmatrix} \in \mathbb{R}^{\dim(\mathbf{q}_{var}^{(l)}) \times \dim(\mathbf{q}_{var}^{(l)})} \quad (2.124)$$

$$\bar{\mathbf{W}}_{adj} := \begin{pmatrix} \bar{\mathbf{I}}_{adj}^{(1)} & -\bar{\mathbf{I}}_{adj}^{(1)} & & \mathbf{O} \\ -\bar{\mathbf{I}}_{adj}^{(1)} & \bar{\mathbf{I}}_{adj}^{(1)} + \bar{\mathbf{I}}_{adj}^{(2)} & -\bar{\mathbf{I}}_{adj}^{(2)} & \\ & & \ddots & \\ \mathbf{O} & & & \bar{\mathbf{I}}_{adj}^{(L-2)} + \bar{\mathbf{I}}_{adj}^{(L-1)} & -\bar{\mathbf{I}}_{adj}^{(L-1)} \\ & & & -\bar{\mathbf{I}}_{adj}^{(L-1)} & \bar{\mathbf{I}}_{adj}^{(L-1)} \end{pmatrix} \in \mathbb{R}^{\dim(\mathbf{q}_{var}) \times \dim(\mathbf{q}_{var})} \quad (2.125)$$

$$\mathbf{W}_{adj} := \begin{pmatrix} \bar{\mathbf{W}}_{adj} \\ \mathbf{O} \end{pmatrix} \quad (2.126)$$

return $\mathbf{W}_{adj} \in \mathbb{R}^{\dim(\mathbf{q}) \times \dim(\mathbf{q})}$

:adjacent-regular-vector *ℰkey (update? t)* [method]

$$\mathbf{v}_{adj} := \mathbf{W}_{adj} \mathbf{q} \quad (2.127)$$

return $\mathbf{v}_{adj} \in \mathbb{R}^{\dim(\mathbf{q})}$

:torque-regular-matrix *ℰkey (update? nil)* [method]

$$\bar{\mathbf{W}}_{trq} := \begin{pmatrix} \mathbf{W}_{trq}^{(1)} & & & \mathbf{O} \\ & \mathbf{W}_{trq}^{(2)} & & \\ & & \ddots & \\ \mathbf{O} & & & \mathbf{W}_{trq}^{(L)} \end{pmatrix} \in \mathbb{R}^{\dim(\mathbf{q}_{var}) \times \dim(\mathbf{q}_{var})} \quad (2.128)$$

$$\mathbf{W}_{trq} := \begin{pmatrix} \bar{\mathbf{W}}_{trq} \\ \mathbf{O} \end{pmatrix} \quad (2.129)$$

return $\mathbf{W}_{trq} \in \mathbb{R}^{\dim(\mathbf{q}) \times \dim(\mathbf{q})}$

:torque-regular-vector *ℰkey (update? t)* [method]

$$\bar{\mathbf{v}}_{trq} := \begin{pmatrix} \mathbf{v}_{trq}^{(1)} \\ \mathbf{v}_{trq}^{(2)} \\ \vdots \\ \mathbf{v}_{trq}^{(L)} \end{pmatrix} \in \mathbb{R}^{\dim(\mathbf{q}_{var})} \quad (2.130)$$

$$\mathbf{v}_{trq} := \begin{pmatrix} \bar{\mathbf{v}}_{trq} \\ \mathbf{0} \end{pmatrix} \quad (2.131)$$

return $\mathbf{v}_{trq} \in \mathbb{R}^{dim(\mathbf{q})}$

:regular-matrix [method]

$$\mathbf{W}_{reg} := \min(k_{max}, \|\mathbf{e}\|^2 + k_{off})\mathbf{I} + \mathbf{W}_{adj} + k_{trq}\mathbf{W}_{trq} \quad (2.132)$$

return $\mathbf{W}_{reg} \in \mathbb{R}^{dim(\mathbf{q}) \times dim(\mathbf{q})}$

:regular-vector [method]

$$\mathbf{v}_{reg} := \mathbf{v}_{adj} + k_{trq}\mathbf{v}_{trq} \quad (2.133)$$

return $\mathbf{v}_{reg} \in \mathbb{R}^{dim(\mathbf{q})}$

:update-viewer [method]

Update viewer.

:print-status [method]

Print status.

:play-animation *key* (*robot-env*) [method]

(*loop?* *t*)

(*visualize-callback-func*)

Play motion.

:generate-robot-state-list *key* (*robot-env*) [method]

(*joint-name-list* (*send-all* (*send robot-env :robot :joint-list*) *:name*))

(*root-link-name* (*send* (*car* (*send robot-env :robot :links*)) *:name*))

(*step-time* 0.004)

(*divide-num* 100)

(*limb-list* (*list :rleg :lleg :rarm :larm*))

Generate and return robot state list.

3 勾配を用いた制約付き非線形最適化

3.1 逐次二次計画法

sqp-optimization [class]

:super **propertied-object**

:slots (*_config-task* instance of configuration-task)

(*_qp-retval* buffer for QP return value)

(*_qp-status* buffer for QP status)

(*_qp-int-status* QP status)

(*_task-value* buffer for task value $\mathbf{e}(\mathbf{q})$)

(*_task-jacobian* buffer for task jacobian $\frac{\partial \mathbf{e}}{\partial \mathbf{q}}$)

(.dim-config-buf-matrix matrix buffer)
 (.convergence-check-func function to check convergence)
 (.failure-callback-func callback function of failure)
 (.pre-process-func pre-process function)
 (.post-process-func post-process function)
 (.i buffer for iteration count)
 (.status status of sqp optimization)
 (.no-visualize? whether to suppress visualization)
 (.no-print? whether to suppress print)

逐次二次計画法のクラス .

instant-configuration-task クラスや trajectory-configuration-task クラスの instance (以降, configuration-task と呼ぶ) が与えられた時に, configuration-task のタスク関数ノルム二乗 $\|e(q)\|^2$ を最小にするコンフィギュレーション q を反復計算により求める .

:init *ℰkey (config-task)* [method]
(convergence-check-func)
(failure-callback-func)
(pre-process-func)
(post-process-func)
(no-visualize?)
(no-print?)
ℰallow-other-keys

Initialize instance

:config-task [method]
 Return configuration-task instance

:optimize *ℰkey (loop-num 100)* [method]
(loop-num-min)
(update-viewer-interval 1)
(print-status-interval 10)

Optimize

In each iteration, do following:

1. check convergence
2. call pre-process function
3. print status
4. solve QP and update configuration
5. call post-process function

Solve following QP:

$$\min_{\Delta \mathbf{q}^{(k)}} \frac{1}{2} \Delta \mathbf{q}^{(k)T} \mathbf{W} \Delta \mathbf{q}^{(k)} + \mathbf{v}^T \Delta \mathbf{q}^{(k)} \quad (3.1)$$

$$\text{s.t. } \mathbf{A} \Delta \mathbf{q}^{(k)} = \mathbf{b} \quad (3.2)$$

$$\mathbf{C} \Delta \mathbf{q}^{(k)} \geq \mathbf{d} \quad (3.3)$$

$$\text{where } \mathbf{W} = \left(\frac{\partial \mathbf{e}(\mathbf{q}^{(k)})}{\partial \mathbf{q}^{(k)}} \right)^T \left(\frac{\partial \mathbf{e}(\mathbf{q}^{(k)})}{\partial \mathbf{q}^{(k)}} \right) + \mathbf{W}_{reg} \quad (3.4)$$

$$\mathbf{v} = \left(\frac{\partial \mathbf{e}(\mathbf{q}^{(k)})}{\partial \mathbf{q}^{(k)}} \right)^T \mathbf{e}(\mathbf{q}^{(k)}) + \mathbf{v}_{reg} \quad (3.5)$$

and update configuration:

$$\mathbf{q}^{(k+1)} = \mathbf{q}^{(k)} + \Delta \mathbf{q}^{(k)*} \quad (3.6)$$

:iteration [method]

Return iteration index.

:status [method]

Return status of sqp optimization.

3.2 複数解候補を用いた逐次二次計画法

3.2.1 複数解候補を用いた逐次二次計画法の理論

式 (1.4a) の最適化問題に逐次二次計画法などの制約付き非線形最適化手法を適用すると、初期値から勾配方向に進行して至る局所最適解が得られると考えられる。したがって解は初期値に強く依存する。

式 (1.4a) の代わりに、以下の最適化問題を考える。

$$\min_{\hat{\mathbf{q}}} \sum_{i \in \mathcal{I}} \left\{ F(\mathbf{q}^{(i)}) + k_{msc} F_{msc}(\hat{\mathbf{q}}; i) \right\} \quad (3.7)$$

$$\text{s.t. } \mathbf{A} \mathbf{q}^{(i)} = \bar{\mathbf{b}} \quad i \in \mathcal{I} \quad (3.8)$$

$$\mathbf{C} \mathbf{q}^{(i)} \geq \bar{\mathbf{d}} \quad i \in \mathcal{I} \quad (3.9)$$

$$\text{where } \hat{\mathbf{q}} \stackrel{\text{def}}{=} \left(\mathbf{q}^{(1)T} \quad \mathbf{q}^{(2)T} \quad \dots \quad \mathbf{q}^{(N_{msc})T} \right)^T \quad (3.10)$$

$$\mathcal{I} \stackrel{\text{def}}{=} \{1, 2, \dots, N_{msc}\} \quad (3.11)$$

$$F_{msc}(\hat{\mathbf{q}}; i) \stackrel{\text{def}}{=} -\frac{1}{2} \sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \log \|d(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2 \quad (3.12)$$

$$d(\mathbf{q}^{(i)}, \mathbf{q}^{(j)}) \stackrel{\text{def}}{=} \mathbf{q}^{(i)} - \mathbf{q}^{(j)} \quad (3.13)$$

N_{msc} は解候補の個数で、事前に与えるものとする。 msc は複数解候補 (multiple solution candidates) を表す。これは、複数の解候補を同時に探索し、それぞれの解候補 $\mathbf{q}^{(i)}$ が本来の目的関数 $F(\mathbf{q}^{(i)})$ を小さくして、なおかつ、解候補どうしの距離が大きくなるように最適化することを表している。これにより、初期値に依存した唯一の局所解だけでなく、そこから離れた複数の局所解を得ることが可能となり、通常の最適化に比べてより良い解が得られることが期待される。以降では、解候補どうしの距離のコストを表す項 $F_{msc}(\hat{\mathbf{q}}; i)$ を解候補分散項と呼ぶ⁸。

⁸ 解分散項の \log を無くすことは適切ではない。なぜなら、 $d = \|d(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|$ として、解分散項の勾配は、

$$\frac{\partial}{\partial d} \left(-\frac{1}{2} \log d^2 \right) = -\frac{1}{d} \rightarrow -\infty \quad (d \rightarrow +0) \quad \frac{\partial}{\partial d} \left(-\frac{1}{2} \log d^2 \right) = -\frac{1}{d} \rightarrow 0 \quad (d \rightarrow \infty) \quad (3.14)$$

解候補分散項のヤコビ行列，ヘッセ行列の各成分は次式で得られる⁹．

$$\nabla_i F_{msc}(\hat{\mathbf{q}}; i) = \frac{\partial F_{msc}(\hat{\mathbf{q}}; i)}{\partial \mathbf{q}^{(i)}} \quad (3.16a)$$

$$= -\frac{1}{2} \sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \frac{\partial}{\partial \mathbf{q}^{(i)}} \log \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2 \quad (3.16b)$$

$$= -\sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \frac{1}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2} \left(\frac{\partial \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})}{\partial \mathbf{q}^{(i)}} \right)^T \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)}) \quad (3.16c)$$

$$= -\sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \frac{\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2} \quad (3.16d)$$

$$(3.16e)$$

$$\nabla_k F_{msc}(\hat{\mathbf{q}}; i) = \frac{\partial F_{msc}(\hat{\mathbf{q}}; i)}{\partial \mathbf{q}^{(k)}} \quad k \in \mathcal{I} \wedge k \neq i \quad (3.17a)$$

$$= -\frac{1}{2} \sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \frac{\partial}{\partial \mathbf{q}^{(k)}} \log \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2 \quad (3.17b)$$

$$= -\frac{1}{2} \frac{\partial}{\partial \mathbf{q}^{(k)}} \log \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^2 \quad (3.17c)$$

$$= -\frac{1}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^2} \left(\frac{\partial \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})}{\partial \mathbf{q}^{(k)}} \right)^T \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)}) \quad (3.17d)$$

$$= \frac{\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^2} \quad (3.17e)$$

$$(3.17f)$$

$$\nabla_{ii}^2 F_{msc}(\hat{\mathbf{q}}; i) = \frac{\partial^2 F_{msc}(\hat{\mathbf{q}}; i)}{\partial \mathbf{q}^{(i)2}} \quad (3.18a)$$

$$= -\sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \frac{\partial}{\partial \mathbf{q}^{(i)}} \left(\left\{ \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2 \right\}^{-1} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)}) \right) \quad (3.18b)$$

$$= -\sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \left(-2 \left\{ \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2 \right\}^{-2} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)}) \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})^T + \left\{ \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2 \right\}^{-1} \mathbf{I} \right) \quad (3.18c)$$

$$= -\sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \left(-\frac{2}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^4} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)}) \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})^T + \frac{1}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2} \mathbf{I} \right) \quad (3.18d)$$

$$= -\sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \mathbf{H}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)}) \quad (3.18e)$$

となり，最適化により，コンフィギュレーションが近いときほど離れるように更新し，遠くなるとその影響が小さくなる効果が期待される．それに対し， \log が無い場合の勾配は，

$$\frac{\partial}{\partial d} \left(-\frac{1}{2} d^2 \right) = -d \rightarrow 0 \quad (d \rightarrow +0) \quad \frac{\partial}{\partial d} \left(-\frac{1}{2} d^2 \right) = -d \rightarrow -\infty \quad (d \rightarrow \infty) \quad (3.15)$$

となり，コンフィギュレーションが遠くなるほど離れるように更新し，近いときはその影響が小さくなる．これは，コンフィギュレーションが一致する勾配ゼロの点と，無限に離れ発散する最適値をもち，これらは最適化において望まない挙動をもたらす．

⁹ヘッセ行列の導出は以下を参考にした．<https://math.stackexchange.com/questions/175263/gradient-and-hessian-of-general-2-norm>

ただし ,

$$\mathbf{H}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)}) \stackrel{\text{def}}{=} -\frac{2}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^4} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)}) \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})^T + \frac{1}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2} \mathbf{I} \quad (3.19)$$

$$\nabla_{ik}^2 F_{msc}(\hat{\mathbf{q}}; i) = \frac{\partial^2 F_{msc}(\hat{\mathbf{q}}; i)}{\partial \mathbf{q}^{(i)} \partial \mathbf{q}^{(k)}} \quad k \in \mathcal{I} \wedge k \neq i \quad (3.20a)$$

$$= -\sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \frac{\partial}{\partial \mathbf{q}^{(k)}} \left(\left\{ \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2 \right\}^{-1} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)}) \right) \quad (3.20b)$$

$$= -\frac{\partial}{\partial \mathbf{q}^{(k)}} \left(\left\{ \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^2 \right\}^{-1} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)}) \right) \quad (3.20c)$$

$$= -\left(2 \left\{ \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^2 \right\}^{-2} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)}) \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})^T - \left\{ \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^2 \right\}^{-1} \mathbf{I} \right) \quad (3.20d)$$

$$= -\frac{2}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^4} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)}) \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})^T + \frac{1}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^2} \mathbf{I} \quad (3.20e)$$

$$= \mathbf{H}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)}) \quad (3.20f)$$

$$\nabla_{kk}^2 F_{msc}(\hat{\mathbf{q}}; i) = \frac{\partial^2 F_{msc}(\hat{\mathbf{q}}; i)}{\partial \mathbf{q}^{(k)2}} \quad k \in \mathcal{I} \wedge k \neq i \quad (3.21a)$$

$$= \frac{\partial}{\partial \mathbf{q}^{(k)}} \left(\left\{ \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^2 \right\}^{-1} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)}) \right) \quad (3.21b)$$

$$= -\left(-\frac{2}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^4} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)}) \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})^T + \frac{1}{\|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^2} \mathbf{I} \right) \quad (3.21c)$$

$$= -\mathbf{H}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)}) \quad (3.21d)$$

$$\nabla_{kl}^2 F_{msc}(\hat{\mathbf{q}}; i) = \frac{\partial^2 F_{msc}(\hat{\mathbf{q}}; i)}{\partial \mathbf{q}^{(k)} \partial \mathbf{q}^{(l)}} \quad k \in \mathcal{I} \wedge l \in \mathcal{I} \wedge k \neq i \wedge l \neq i \wedge k \neq l \quad (3.22a)$$

$$= \frac{\partial}{\partial \mathbf{q}^{(l)}} \left(\left\{ \|\mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)})\|^2 \right\}^{-1} \mathbf{d}(\mathbf{q}^{(i)}, \mathbf{q}^{(k)}) \right) \quad (3.22b)$$

$$= \mathbf{O} \quad (3.22c)$$

したがって，解候補分散項のヤコビ行列，ヘッセ行列は次式で表される．

$$\nabla F_{msc}(\hat{\mathbf{q}}; i) = \frac{\partial F_{msc}(\hat{\mathbf{q}}; i)}{\partial \hat{\mathbf{q}}} \quad (3.23a)$$

$$= \begin{pmatrix} \frac{d(\mathbf{q}^{(i)}, \mathbf{q}^{(1)})}{\|d(\mathbf{q}^{(i)}, \mathbf{q}^{(1)})\|^2} \\ \vdots \\ \frac{d(\mathbf{q}^{(i)}, \mathbf{q}^{(i-1)})}{\|d(\mathbf{q}^{(i)}, \mathbf{q}^{(i-1)})\|^2} \\ - \sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \frac{d(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})}{\|d(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})\|^2} \\ \frac{d(\mathbf{q}^{(i)}, \mathbf{q}^{(i+1)})}{\|d(\mathbf{q}^{(i)}, \mathbf{q}^{(i+1)})\|^2} \\ \vdots \\ \frac{d(\mathbf{q}^{(i)}, \mathbf{q}^{(N_{msc})})}{\|d(\mathbf{q}^{(i)}, \mathbf{q}^{(N_{msc})})\|^2} \end{pmatrix} \quad (3.23b)$$

$$\mathbf{v}_{msc} \stackrel{\text{def}}{=} \sum_{i \in \mathcal{I}} \nabla F_{msc}(\hat{\mathbf{q}}; i) \quad (3.23c)$$

$$= 2 \begin{pmatrix} - \sum_{\substack{j \in \mathcal{I} \\ j \neq 1}} \frac{d(\mathbf{q}^{(1)}, \mathbf{q}^{(j)})}{\|d(\mathbf{q}^{(1)}, \mathbf{q}^{(j)})\|^2} \\ \vdots \\ - \sum_{\substack{j \in \mathcal{I} \\ j \neq N_{msc}}} \frac{d(\mathbf{q}^{(N_{msc})}, \mathbf{q}^{(j)})}{\|d(\mathbf{q}^{(N_{msc})}, \mathbf{q}^{(j)})\|^2} \end{pmatrix} \quad (3.23d)$$

$$\nabla^2 F_{msc}(\hat{\mathbf{q}}; i) = \frac{\partial^2 F_{msc}(\hat{\mathbf{q}}; i)}{\partial \hat{\mathbf{q}}^2} \quad (3.24a)$$

$$= \begin{matrix} & 1 & \cdots & i-1 & i & i+1 & \cdots & N_{msc} \\ \begin{matrix} 1 \\ \vdots \\ i-1 \\ i \\ i+1 \\ \vdots \\ N_{msc} \end{matrix} & \begin{pmatrix} -\mathbf{H}_{i,1} & & & \mathbf{H}_{i,1} & & & \\ & \ddots & & \vdots & & & \\ & & -\mathbf{H}_{i,i-1} & \mathbf{H}_{i,i-1} & & & \\ \mathbf{H}_{i,1} & \cdots & \mathbf{H}_{i,i-1} & - \sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \mathbf{H}_{i,j} & \mathbf{H}_{i,i+1} & \cdots & \mathbf{H}_{i,N_{msc}} \\ & & & \mathbf{H}_{i,i+1} & -\mathbf{H}_{i,i+1} & & \\ & & & \vdots & & \ddots & \\ & & & \mathbf{H}_{i,N_{msc}} & & & -\mathbf{H}_{i,N_{msc}} \end{pmatrix} \end{matrix} \quad (3.24b)$$

$$\mathbf{W}_{msc} \stackrel{\text{def}}{=} \sum_{i \in \mathcal{I}} \nabla^2 F_{msc}(\hat{\mathbf{q}}; i) \quad (3.24c)$$

$$= 2 \begin{pmatrix} - \sum_{\substack{j \in \mathcal{I} \\ j \neq 1}} \mathbf{H}_{1,j} & \mathbf{H}_{1,2} & \cdots & \mathbf{H}_{1,N_{msc}} \\ \mathbf{H}_{2,1} & - \sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \mathbf{H}_{2,j} & & \mathbf{H}_{2,N_{msc}} \\ \vdots & & \ddots & \vdots \\ \mathbf{H}_{N_{msc},1} & \mathbf{H}_{N_{msc},2} & \cdots & - \sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \mathbf{H}_{N_{msc},j} \end{pmatrix} \quad (3.24d)$$

ただし， $\mathbf{H}(\mathbf{q}^{(i)}, \mathbf{q}^{(j)})$ を $\mathbf{H}_{i,j}$ と略して記す．また， $d(\mathbf{q}^{(i)}, \mathbf{q}^{(j)}) = -d(\mathbf{q}^{(j)}, \mathbf{q}^{(i)})$ ， $\mathbf{H}_{i,j} = \mathbf{H}_{j,i}$ を利用した．

解候補分散項 $\sum_{i \in \mathcal{I}} F_{msc}(\hat{\mathbf{q}}; i)$ による二次計画問題の目的関数 (式 (1.5a)) は次式で表される．

$$\sum_{i \in \mathcal{I}} \left\{ F_{msc}(\hat{\mathbf{q}}_k; i) + \nabla F_{msc}(\hat{\mathbf{q}}_k; i)^T \Delta \hat{\mathbf{q}}_k + \frac{1}{2} \Delta \hat{\mathbf{q}}_k^T \nabla^2 F_{msc}(\hat{\mathbf{q}}_k; i) \Delta \hat{\mathbf{q}}_k \right\} \quad (3.25)$$

$$= \sum_{i \in \mathcal{I}} F_{msc}(\hat{\mathbf{q}}_k; i) + \left\{ \sum_{i \in \mathcal{I}} \nabla F_{msc}(\hat{\mathbf{q}}_k; i) \right\}^T \Delta \hat{\mathbf{q}}_k + \frac{1}{2} \Delta \hat{\mathbf{q}}_k^T \left\{ \sum_{i \in \mathcal{I}} \nabla^2 F_{msc}(\hat{\mathbf{q}}_k; i) \right\} \Delta \hat{\mathbf{q}}_k \quad (3.26)$$

$$= \sum_{i \in \mathcal{I}} F_{msc}(\hat{\mathbf{q}}_k; i) + \mathbf{v}_{msc}^T \Delta \hat{\mathbf{q}}_k + \frac{1}{2} \Delta \hat{\mathbf{q}}_k^T \mathbf{W}_{msc} \Delta \hat{\mathbf{q}}_k \quad (3.27)$$

W_{msc} が必ずしも半正定値行列ではないことに注意する必要がある．以下のようにして W_{msc} に近い正定値行列を計算し用いることで対処する¹⁰． W_{msc} が次式のように固有値分解されるとする．

$$W_{msc} = V_{msc} D_{msc} V_{msc}^{-1} \quad (3.28)$$

ただし， D_{msc} は固有値を対角成分にもつ対角行列， V_{msc} は固有ベクトルを並べた行列である．このとき W_{msc} に近い正定値行列 \tilde{W}_{msc} は次式で得られる．

$$\tilde{W}_{msc} = V_{msc} D_{msc}^+ V_{msc}^{-1} \quad (3.29)$$

ただし， D_{msc}^+ は D_{msc} の対角成分のうち，負のものを 0 で置き換えた対角行列である．

式 (3.7) において，解候補を分散させながら，最終的に本来の目的関数を最小にする解を得るために，SQP のイテレーションごとに，解候補分散項のスケール k_{msc} を次式のように更新することが有効である．

$$k_{msc} \leftarrow \min(\gamma_{msc} k_{msc}, k_{msc-min}) \quad (3.30)$$

γ_{msc} は $0 < \gamma_{msc} < 1$ なるスケール減少率， $k_{msc-min}$ はスケール最小値を表す．

3.2.2 複数解候補を用いた逐次二次計画法の実装

sqp-msc-optimization

[class]

```

:super      sqp-optimization
:slots      (_num-msc number of multiple solution candidates  $N_{msc}$ )
              (_config-task-list list of configuration-task instance)
              (_dispersion-scale  $k_{msc}$ )
              (_dispersion-scale-min  $k_{msc-min}$ , minimum of  $k_{msc}$ )
              (_dispersion-scale-decrease-ratio  $\gamma_{msc}$ , decrease ration of  $k_{msc}$ )
              (_config-vector-dist2-min minimum squared distance of configuration vector)
              (_dispersion-matrix buffer for  $W_{msc}$ )

```

複数回候補を用いた逐次二次計画法のクラス．

instant-configuration-task クラスや trajectory-configuration-task クラスの instance (以降, configuration-task と呼ぶ) が与えられた時に, configuration-task のタスク関数ノルム二乗 $\|e(q)\|^2$ を最小にするコンフィギュレーション q を, 複数の解候補を同時に考慮しながら反復計算により求める．

```

:init &rest args &key (num-msc 3) [method]
      (dispersion-scale 0.01)
      (dispersion-scale-min 0.0)
      (dispersion-scale-decrease-ratio 0.5)
      (config-vector-dist2-min 1.000000e-10)
      &allow-other-keys

```

Initialize instance

```

:config-task-list [method]

```

Return list of configuration-task instance

¹⁰ W_{msc} が対称行列であることから, 以下を参考にした．https://math.stackexchange.com/questions/648809/how-to-find-closest-positive-definite-matrix-of-non-symmetric-matrix#comment1689831_649522

:dispersion-matrix [method]

式 (3.23d) 参照 .

return $\mathbf{W}_{msc} \in \mathbb{R}^{N_{msc} \dim(\mathbf{q}) \times N_{msc} \dim(\mathbf{q})}$

:dispersion-vector [method]

式 (3.24d) 参照 .

return $\mathbf{v}_{msc} \in \mathbb{R}^{N_{msc} \dim(\mathbf{q})}$

4 動作生成の拡張

4.1 マニピュレーションの動作生成

robot-object-environment [class]

```

:super      robot-environment
:slots      (_obj  $\mathcal{O}$ )
             (_obj-with-root-virtual  $\hat{\mathcal{O}}$ )

```

ロボットと物体とロボット・環境間の接触のクラス .

以下を合わせた関節・リンク構造に関するメソッドが定義されている .

1. 浮遊ルートリンクのための仮想関節付きのロボットの関節
2. 物体位置姿勢を表す仮想関節
3. 接触位置を定める仮想関節

関節・リンク構造を定めるために、初期化時に以下を与える

robot \mathcal{R} ロボット (cascaded-link クラスのインスタンス) .

object \mathcal{O} 物体 (cascaded-link クラスのインスタンス) . 関節をもたないことを前提とする .

contact-list $\{\mathcal{C}_1, \mathcal{C}_2, \dots, \mathcal{C}_{N_C}\}$ 接触 (2d-planar-contact クラスなどのインスタンス) のリスト .

ロボット \mathcal{R} に、浮遊ルートリンクの変位に対応する仮想関節を付加した仮想関節付きロボット $\hat{\mathcal{R}}$ を内部で保持する . 同様に、物体 \mathcal{O} に、物体の変位に対応する仮想関節を付加した仮想関節付き物体 $\hat{\mathcal{O}}$ を内部で保持する .

:init \mathcal{E}_{key} (*robot*) [method]

```

(object)
(contact-list)
(root-virtual-mode :6dof)
(root-virtual-joint-class-list)
(root-virtual-joint-axis-list)

```

Initialize instance

:object \mathcal{E}_{rest} *args* [method]

return \mathcal{O}

:object-with-root-virtual \mathcal{E}_{rest} *args* [method]

return $\hat{\mathcal{O}}$

instant-manipulation-configuration-task

[class]

```

:super      instant-configuration-task
:slots      (_robot-obj-env robot-object-environment instance)
              (_wrench-obj-vector  $\hat{\mathbf{w}}_{obj}$  [N] [Nm])
              (_num-contact-obj  $N_{cnt-obj} := |\mathcal{T}^{cnt-trg-obj}|$ )
              (_num-act-react  $N_{act-react} := |\mathcal{P}^{act-react}|$ )
              (_dim-wrench-obj  $dim(\hat{\mathbf{w}}_{obj}) = 6N_{cnt-obj}$ )
              (_contact-target-coords-obj-list  $\mathcal{T}^{cnt-trg-obj}$ )
              (_contact-constraint-obj-list list of contact-constraint instance for object)
              (_act-react-pair-list  $\mathcal{P}^{act-react}$ )

```

マニピュレーションにける瞬時コンフィギュレーション $q^{(l)}$ と瞬時タスク関数 $e^{(l)}(q^{(l)})$ のクラス。マニピュレーション対象の物体の瞬時コンフィギュレーションや瞬時タスク関数を含む。

このクラスの説明で用いる全ての変数は、時間ステップ l を表す添字をつけて $x^{(l)}$ と表されるべきだが、このクラス内の説明では省略して x と表す。また、以降では、説明文やメソッド名で、“瞬時” や “instant” を省略する。

コンフィギュレーション q の取得・更新、タスク関数 $e(q)$ の取得、タスク関数のヤコビ行列 $\frac{\partial e(q)}{\partial q}$ の取得、コンフィギュレーションの等式・不等式制約 A, b, C, d の取得のためのメソッドが定義されている。コンフィギュレーション・タスク関数を定めるために、instant-configuration-task の設定に加えて、初期化時に以下を与える

- ロボット・物体・環境
robot-object-environment ロボット・物体・環境を表す robot-object-environment クラスのインスタンス
- 物体の接触拘束
contact-target-coords-obj-list $\mathcal{T}^{cnt-trg-obj}$ 物体の接触目標位置姿勢リスト
contact-constraint-obj-list 物体の接触レンチ制約リスト
- 作用・反作用の拘束
act-react-pair-list $\mathcal{P}^{act-react}$ 作用・反作用の関係にあるロボット・物体の接触目標位置姿勢ペアのリスト

コンフィギュレーション q は以下から構成される。

```

 $\theta \in \mathbb{R}^{N_{var-joint}}$  時変関節角度 [rad] [m]
 $\hat{\mathbf{w}} \in \mathbb{R}^{6N_{cnt}}$  ロボットの接触レンチ [N] [Nm]
 $\hat{\mathbf{w}}_{obj} \in \mathbb{R}^{6N_{cnt-obj}}$  物体の接触レンチ [N] [Nm]
 $\tau \in \mathbb{R}^{N_{drive-joint}}$  関節駆動トルク [Nm] [N]
 $\phi \in \mathbb{R}^{N_{invar-joint}}$  時不変関節角度 [rad] [m]

```

$\hat{\mathbf{w}}$ は次式のように、全接触部位でのワールド座標系での力・モーメントを並べたベクトルである。

$$\hat{\mathbf{w}} = \begin{pmatrix} \mathbf{w}_1^T & \mathbf{w}_2^T & \cdots & \mathbf{w}_{N_{cnt}}^T \end{pmatrix}^T \quad (4.1)$$

$$= \begin{pmatrix} \mathbf{f}_1^T & \mathbf{n}_1^T & \mathbf{f}_2^T & \mathbf{n}_2^T & \cdots & \mathbf{f}_{N_{cnt}}^T & \mathbf{n}_{N_{cnt}}^T \end{pmatrix}^T \quad (4.2)$$

タスク関数 $e(q)$ は以下から構成される.

$$e^{kin}(\mathbf{q}) \in \mathbb{R}^{6N_{kin}} \quad \text{幾何到達拘束} \quad [\text{rad}] \quad [\text{m}]$$

$$e^{eom-trans}(\mathbf{q}) \in \mathbb{R}^3 \text{ ロボットの力の釣り合い [N]}$$

$$\mathbf{e}^{com-rot}(\mathbf{q}) \in \mathbb{R}^3 \text{ ロボットのモーメントの釣り合い [Nm]}$$

$$e^{eom-trans-obj}(\mathbf{q}) \in \mathbb{R}^3 \text{ 物体の力の釣り合い [N]}$$

$$\mathbf{e}^{com-rot-obj}(\mathbf{q}) \in \mathbb{R}^3 \text{ 物体のモーメントの釣り合い } [\text{Nm}]$$

$$\mathbf{e}^{trq}(\mathbf{q}) \in \mathbb{R}^{N_{drive-joint}} \quad \text{関節トルクの釣り合い} \quad [\text{rad}] \quad [\text{m}]$$

$$e^{posture}(\mathbf{q}) \in \mathbb{R}^{N_{posture-joint}} \quad \text{関節角目標 [rad] [m]}$$

```
:init &rest args &key (contact-target-coords-obj-list) [method]
      (contact-constraint-obj-list)
      (act-react-pair-list)
      &allow-other-keys
```

Initialize instance

```
:robot-obj-env [method]
    return robot-object-environment instance
```

```

:wrench-obj [method]
    return  $\hat{\boldsymbol{w}}_{obj}$ 

```

```

:num-contact-obj [method]
    return  $N_{cnt-obj} := |\mathcal{T}^{cnt-trg-obj}|$ 

```

:dim-variant-config [method]

$$\dim(\mathbf{q}_{var}) := \dim(\boldsymbol{\theta}) + \dim(\hat{\mathbf{w}}) + \dim(\hat{\mathbf{w}}_{obj}) + \dim(\boldsymbol{\tau}) \quad (4.3)$$

$$= N_{var-joint} + 6N_{cnt} + 6N_{cnt-obj} + N_{drive-joint} \quad (4.4)$$

```

return  $\dim(\mathbf{q}_{var})$ 

```

:dim-task [method]

$$\begin{aligned} \dim(\mathbf{e}) \quad &:= \dim(\mathbf{e}^{kin}) + \dim(\mathbf{e}^{com-trans}) + \dim(\mathbf{e}^{com-rot}) + \dim(\mathbf{e}^{com-trans-obj}) \\ &+ \dim(\mathbf{e}^{com-rot-obj}) + \dim(\mathbf{e}^{trq}) + \dim(\mathbf{e}^{posture}) \end{aligned} \quad (4.5)$$

$$= 6N_{kin} + 3 + 3 + 3 + 3 + N_{drive-joint} + N_{posture-joint} \quad (4.6)$$

```

return  $\dim(\mathbf{e})$ 

```

```
:variant-config-vector [method]
```

$$\text{return } \mathbf{q}_{var} := \begin{pmatrix} \theta \\ \hat{w} \\ \hat{w}_{obj} \\ \tau \end{pmatrix}$$

```

:config-vector
[method]

```

$$\text{return } \mathbf{q} := \begin{pmatrix} \mathbf{q}_{var} \\ \mathbf{q}_{invar} \end{pmatrix} = \begin{pmatrix} \boldsymbol{\theta} \\ \hat{\mathbf{w}} \\ \hat{\mathbf{w}}_{obj} \\ \boldsymbol{\tau} \\ \boldsymbol{\phi} \end{pmatrix}$$

:set-wrench-obj *wrench-obj-new* *ℰkey* (*relative?* *nil*) [method]
 Set $\hat{\mathbf{w}}_{obj}$.

:set-variant-config *variant-config-new* *ℰkey* (*relative?* *nil*) [method]
 (*apply-to-robot?* *t*)
 Set \mathbf{q}_{var} .

:contact-target-coords-obj-list [method]

$$T_m^{cnt-trg-obj} = \{\mathbf{p}_m^{cnt-trg-obj}, \mathbf{R}_m^{cnt-trg-obj}\} \quad (m = 1, 2, \dots, N_{cnt-obj}) \quad (4.7)$$

$$\text{return } \mathcal{T}^{cnt-trg-obj} := \{T_1^{cnt-trg-obj}, T_2^{cnt-trg-obj}, \dots, T_{N_{cnt-obj}}^{cnt-trg-obj}\}$$

:contact-constraint-obj-list [method]
 return list of contact-constraint instance for object

:wrench-obj-list [method]
 return $\{\mathbf{w}_{obj,1}, \mathbf{w}_{obj,2}, \dots, \mathbf{w}_{obj,N_{obj}}\}$

:force-obj-list [method]
 return $\{\mathbf{f}_{obj,1}, \mathbf{f}_{obj,2}, \dots, \mathbf{f}_{obj,N_{cnt-obj}}\}$

:moment-obj-list [method]
 return $\{\mathbf{n}_{obj,1}, \mathbf{n}_{obj,2}, \dots, \mathbf{n}_{obj,N_{cnt-obj}}\}$

:mg-obj-vec [method]
 return $m_{obj}\mathbf{g}$

:cog-obj *ℰkey* (*update?* *t*) [method]
 return $\mathbf{p}_{Gobj}(\mathbf{q})$

:eom-trans-obj-task-value *ℰkey* (*update?* *t*) [method]

$$\mathbf{e}^{eom-trans-obj}(\mathbf{q}) = \mathbf{e}^{eom-trans-obj}(\hat{\mathbf{w}}_{obj}) \quad (4.8)$$

$$= \sum_{m=1}^{N_{cnt-obj}} \mathbf{f}_{obj,m} - m_{obj}\mathbf{g} \quad (4.9)$$

$$\text{return } \mathbf{e}^{eom-trans-obj}(\mathbf{q}) \in \mathbb{R}^3$$

:eom-rot-obj-task-value *ℰkey* (*update?* *t*) [method]

$$\mathbf{e}^{eom-rot-obj}(\mathbf{q}) = \mathbf{e}^{eom-rot-obj}(\boldsymbol{\theta}, \hat{\mathbf{w}}_{obj}, \boldsymbol{\phi}) \quad (4.10)$$

$$= \sum_{m=1}^{N_{cnt-obj}} \{(\mathbf{p}_m^{cnt-trg-obj}(\boldsymbol{\theta}, \boldsymbol{\phi}) - \mathbf{p}_{Gobj}(\boldsymbol{\theta}, \boldsymbol{\phi})) \times \mathbf{f}_{obj,m} + \mathbf{n}_{obj,m}\} \quad (4.11)$$

return $e^{eom-rot-obj}(\mathbf{q}) \in \mathbb{R}^3$

:task-value \mathcal{E}_{key} (update? t)

[method]

$$\text{return } e(\mathbf{q}) := \begin{pmatrix} e^{kin}(\mathbf{q}) \\ e^{eom-trans}(\mathbf{q}) \\ e^{eom-rot}(\mathbf{q}) \\ e^{eom-trans-obj}(\mathbf{q}) \\ e^{eom-rot-obj}(\mathbf{q}) \\ e^{trq}(\mathbf{q}) \\ e^{posture}(\mathbf{q}) \end{pmatrix} = \begin{pmatrix} e^{kin}(\boldsymbol{\theta}, \phi) \\ e^{eom-trans}(\hat{\mathbf{w}}) \\ e^{eom-rot}(\boldsymbol{\theta}, \hat{\mathbf{w}}, \phi) \\ e^{eom-trans-obj}(\hat{\mathbf{w}}_{obj}) \\ e^{eom-rot-obj}(\boldsymbol{\theta}, \hat{\mathbf{w}}_{obj}, \phi) \\ e^{trq}(\boldsymbol{\theta}, \hat{\mathbf{w}}, \tau, \phi) \\ e^{posture}(\boldsymbol{\theta}) \end{pmatrix}$$

:eom-trans-obj-task-jacobian-with-wrench-obj

[method]

$$\frac{\partial e^{eom-trans-obj}}{\partial \hat{\mathbf{w}}_{obj}} = \begin{pmatrix} \frac{\partial e^{eom-trans-obj}}{\partial \mathbf{f}_{obj,1}} & \frac{\partial e^{eom-trans-obj}}{\partial \mathbf{n}_{obj,1}} & \cdots & \frac{\partial e^{eom-trans-obj}}{\partial \mathbf{f}_{obj,N_{cnt-obj}}} & \frac{\partial e^{eom-trans-obj}}{\partial \mathbf{n}_{obj,N_{cnt-obj}}} \end{pmatrix} \quad (4.12)$$

$$= \begin{pmatrix} \mathbf{I}_3 & \mathbf{O}_3 & \cdots & \mathbf{I}_3 & \mathbf{O}_3 \end{pmatrix} \quad (4.13)$$

return $\frac{\partial e^{eom-trans-obj}}{\partial \hat{\mathbf{w}}_{obj}} \in \mathbb{R}^{3 \times 6N_{cnt-obj}}$

:eom-rot-obj-task-jacobian-with-theta

[method]

$$\frac{\partial e^{eom-rot-obj}}{\partial \boldsymbol{\theta}} = \sum_{m=1}^{N_{cnt-obj}} \left\{ -[\mathbf{f}_{obj,m} \times] \left(\mathbf{J}_{\theta,m}^{cnt-trg-obj}(\boldsymbol{\theta}, \phi) - \mathbf{J}_{Gobj\theta}(\boldsymbol{\theta}, \phi) \right) \right\} \quad (4.14)$$

$$= \left[\left(\sum_{m=1}^{N_{cnt-obj}} \mathbf{f}_{obj,m} \right) \times \right] \mathbf{J}_{Gobj\theta}(\boldsymbol{\theta}, \phi) - \sum_{m=1}^{N_{cnt-obj}} [\mathbf{f}_{obj,m} \times] \mathbf{J}_{\theta,m}^{cnt-trg-obj}(\boldsymbol{\theta}, \phi) \quad (4.15)$$

$\sum_{m=1}^{N_{cnt-obj}} \mathbf{f}_{obj,m} = m_{obj} \mathbf{g}$ つまり , eom-trans-obj-task が成立すると仮定すると次式が成り立つ .

$$\frac{\partial e^{eom-rot-obj}}{\partial \boldsymbol{\theta}} = [m_{obj} \mathbf{g} \times] \mathbf{J}_{Gobj\theta}(\boldsymbol{\theta}, \phi) - \sum_{m=1}^{N_{cnt-obj}} [\mathbf{f}_{obj,m} \times] \mathbf{J}_{\theta,m}^{cnt-trg-obj}(\boldsymbol{\theta}, \phi) \quad (4.16)$$

return $\frac{\partial e^{eom-rot-obj}}{\partial \boldsymbol{\theta}} \in \mathbb{R}^{3 \times N_{var-joint}}$

:eom-rot-obj-task-jacobian-with-wrench-obj

[method]

$$\frac{\partial e^{eom-rot-obj}}{\partial \hat{\mathbf{w}}_{obj}} = \begin{pmatrix} \frac{\partial e^{eom-rot-obj}}{\partial \mathbf{f}_{obj,1}} & \frac{\partial e^{eom-rot-obj}}{\partial \mathbf{n}_{obj,1}} & \cdots & \frac{\partial e^{eom-rot-obj}}{\partial \mathbf{f}_{obj,N_{cnt-obj}}} & \frac{\partial e^{eom-rot-obj}}{\partial \mathbf{n}_{obj,N_{cnt-obj}}} \end{pmatrix} \quad (4.17)$$

$$\frac{\partial e^{eom-rot-obj}}{\partial \mathbf{f}_{obj,m}} = [(\mathbf{p}_m^{cnt-trg-obj}(\boldsymbol{\theta}, \phi) - \mathbf{p}_{Gobj}(\boldsymbol{\theta}, \phi)) \times] \quad (m = 1, 2, \dots, N_{cnt-obj}) \quad (4.18)$$

$$\frac{\partial e^{eom-rot-obj}}{\partial \mathbf{n}_{obj,m}} = \mathbf{I}_3 \quad (m = 1, 2, \dots, N_{cnt-obj}) \quad (4.19)$$

return $\frac{\partial e^{eom-rot-obj}}{\partial \hat{\mathbf{w}}_{obj}} \in \mathbb{R}^{3 \times 6N_{cnt-obj}}$

:eom-rot-obj-task-jacobian-with-phi

[method]

$$\frac{\partial \mathbf{e}^{eom-rot-obj}}{\partial \phi} = \sum_{m=1}^{N_{cnt-obj}} \left\{ -[\mathbf{f}_{obj,m} \times] \left(\mathbf{J}_{\phi,m}^{cnt-trg-obj}(\boldsymbol{\theta}, \phi) - \mathbf{J}_{Gobj\phi}(\boldsymbol{\theta}, \phi) \right) \right\} \quad (4.20)$$

$$= \left[\left(\sum_{m=1}^{N_{cnt-obj}} \mathbf{f}_{obj,m} \right) \times \right] \mathbf{J}_{Gobj\phi}(\boldsymbol{\theta}, \phi) - \sum_{m=1}^{N_{cnt-obj}} [\mathbf{f}_{obj,m} \times] \mathbf{J}_{\phi,m}^{cnt-trg-obj}(\boldsymbol{\theta}, \phi) \quad (4.21)$$

$\sum_{m=1}^{N_{cnt-obj}} \mathbf{f}_{obj,m} = m_{obj} \mathbf{g}$ つまり, eom-trans-obj-task が成立すると仮定すると次式が成り立つ.

$$\frac{\partial \mathbf{e}^{eom-rot-obj}}{\partial \phi} = [m_{obj} \mathbf{g} \times] \mathbf{J}_{Gobj\phi}(\boldsymbol{\theta}, \phi) - \sum_{m=1}^{N_{cnt-obj}} [\mathbf{f}_{obj,m} \times] \mathbf{J}_{\phi,m}^{cnt-trg-obj}(\boldsymbol{\theta}, \phi) \quad (4.22)$$

return $\frac{\partial \mathbf{e}^{eom-rot-obj}}{\partial \phi} \in \mathbb{R}^{3 \times N_{invar-joint}}$

:variant-task-jacobian

[method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{var}} = \begin{matrix} & N_{var-joint} & 6N_{cnt} & 6N_{cnt-obj} & N_{drive-joint} \\ \begin{matrix} 6N_{kin} \\ 3 \\ 3 \\ 3 \\ 3 \\ N_{drive-joint} \\ N_{posture-joint} \end{matrix} & \begin{pmatrix} \frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\theta}} & & & \\ & \frac{\partial \mathbf{e}^{eom-trans}}{\partial \hat{\mathbf{w}}} & & \\ & \frac{\partial \mathbf{e}^{eom-rot}}{\partial \boldsymbol{\theta}} & \frac{\partial \hat{\mathbf{w}}}{\partial \mathbf{e}^{eom-rot}} & \\ & & \frac{\partial \mathbf{e}^{eom-trans-obj}}{\partial \hat{\mathbf{w}}_{obj}} & \\ & \frac{\partial \mathbf{e}^{eom-rot-obj}}{\partial \boldsymbol{\theta}} & \frac{\partial \hat{\mathbf{w}}_{obj}}{\partial \mathbf{e}^{eom-rot-obj}} & \\ & \frac{\partial \mathbf{e}^{trq}}{\partial \boldsymbol{\theta}} & \frac{\partial \mathbf{e}^{trq}}{\partial \hat{\mathbf{w}}} & \\ & \frac{\partial \mathbf{e}^{posture}}{\partial \boldsymbol{\theta}} & & \frac{\partial \mathbf{e}^{trq}}{\partial \boldsymbol{\tau}} \end{pmatrix} \end{matrix} \quad (4.23)$$

return $\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{var}} \in \mathbb{R}^{(6N_{kin}+3+3+3+3+N_{drive-joint}+N_{posture-joint}) \times (N_{var-joint}+6N_{cnt}+6N_{cnt-obj}+N_{drive-joint})}$

:invariant-task-jacobian

[method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{invar}} = \begin{matrix} & N_{invar-joint} \\ \begin{matrix} 6N_{kin} \\ 3 \\ 3 \\ 3 \\ 3 \\ N_{drive-joint} \\ N_{posture-joint} \end{matrix} & \begin{pmatrix} \frac{\partial \mathbf{e}^{kin}}{\partial \phi} \\ & \frac{\partial \mathbf{e}^{eom-rot}}{\partial \phi} \\ & & \frac{\partial \mathbf{e}^{eom-rot-obj}}{\partial \phi} \\ & & \frac{\partial \mathbf{e}^{trq}}{\partial \phi} \end{pmatrix} \end{matrix} \quad (4.24)$$

return $\frac{\partial \mathbf{e}}{\partial \mathbf{q}_{invar}} \in \mathbb{R}^{(6N_{kin}+3+3+3+3+N_{drive-joint}+N_{posture-joint}) \times N_{invar-joint}}$

:task-jacobian

[method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}} = \begin{pmatrix} \frac{\partial \mathbf{e}}{\partial \mathbf{q}_{\text{var}}} & \frac{\partial \mathbf{e}}{\partial \mathbf{q}_{\text{invar}}} \end{pmatrix} \quad (4.25)$$

$$= \begin{matrix} 6N_{kin} \\ 3 \\ 3 \\ 3 \\ 3 \\ N_{drive-joint} \\ N_{posture-joint} \end{matrix} \begin{pmatrix} N_{var-joint} & 6N_{cnt} & 6N_{cnt-obj} & N_{drive-joint} & N_{invar-joint} \\ \frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\theta}} & & & & \frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\phi}} \\ & \frac{\partial \mathbf{e}^{com-trans}}{\partial \hat{\mathbf{w}}} & & & \\ \frac{\partial \mathbf{e}^{com-rot}}{\partial \boldsymbol{\theta}} & \frac{\partial \mathbf{e}^{com-rot}}{\partial \hat{\mathbf{w}}} & & & \frac{\partial \mathbf{e}^{com-rot}}{\partial \boldsymbol{\phi}} \\ & & \frac{\partial \mathbf{e}^{com-trans-obj}}{\partial \hat{\mathbf{w}}_{obj}} & & \\ \frac{\partial \mathbf{e}^{com-rot-obj}}{\partial \boldsymbol{\theta}} & & \frac{\partial \mathbf{e}^{com-rot-obj}}{\partial \hat{\mathbf{w}}_{obj}} & & \frac{\partial \mathbf{e}^{com-rot-obj}}{\partial \boldsymbol{\phi}} \\ \frac{\partial \mathbf{e}^{trq}}{\partial \boldsymbol{\theta}} & \frac{\partial \mathbf{e}^{trq}}{\partial \hat{\mathbf{w}}} & & \frac{\partial \mathbf{e}^{trq}}{\partial \boldsymbol{\tau}} & \frac{\partial \mathbf{e}^{trq}}{\partial \boldsymbol{\phi}} \\ \frac{\partial \mathbf{e}^{posture}}{\partial \boldsymbol{\theta}} & & & & \end{pmatrix} \quad (4.26)$$

$$\text{return } \frac{\partial \mathbf{e}}{\partial \mathbf{q}} \in \mathbb{R}^{(6N_{kin}+3+3+3+3+N_{drive-joint}+N_{posture-joint}) \times (N_{var-joint}+6N_{cnt}+6N_{cnt-obj}+N_{drive-joint}+N_{invar-joint})}$$

:wrench-obj-inequality-constraint-matrix *ℰkey (update? t)* [method]

物体の接触レンチ $\mathbf{w}_{obj} \in \mathbb{R}^6$ が満たすべき制約（非負制約，摩擦制約，圧力中心制約）が次式のように表されるとする．

$$\mathbf{C}_{w_{obj}} \mathbf{w}_{obj} \geq \mathbf{d}_{w_{obj}} \quad (4.27)$$

$N_{cnt-obj}$ 箇所の接触部位の接触レンチを並べたベクトル $\hat{\mathbf{w}}_{obj}$ の不等式制約は次式で表される．

$$\mathbf{C}_{w_{obj},m} (\mathbf{w}_{obj,m} + \Delta \mathbf{w}_{obj,m}) \geq \mathbf{d}_{w_{obj},m} \quad (m = 1, 2, \dots, N_{cnt-obj}) \quad (4.28)$$

$$\Leftrightarrow \mathbf{C}_{w_{obj},m} \Delta \mathbf{w}_{obj,m} \geq \mathbf{d}_{w_{obj},m} - \mathbf{C}_{w_{obj},m} \mathbf{w}_{obj,m} \quad (m = 1, 2, \dots, N_{cnt-obj}) \quad (4.29)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{C}_{w_{obj},1} & & & \\ & \mathbf{C}_{w_{obj},2} & & \\ & & \ddots & \\ & & & \mathbf{C}_{w_{obj},N_{cnt-obj}} \end{pmatrix} \begin{pmatrix} \Delta \mathbf{w}_{obj,1} \\ \Delta \mathbf{w}_{obj,2} \\ \vdots \\ \Delta \mathbf{w}_{obj,N_{cnt-obj}} \end{pmatrix} \geq \begin{pmatrix} \mathbf{d}_{w_{obj},1} - \mathbf{C}_{w_{obj},1} \mathbf{w}_{obj,1} \\ \mathbf{d}_{w_{obj},2} - \mathbf{C}_{w_{obj},2} \mathbf{w}_{obj,2} \\ \vdots \\ \mathbf{d}_{w_{obj},N_{cnt-obj}} - \mathbf{C}_{w_{obj},N_{cnt-obj}} \mathbf{w}_{obj,N_{cnt-obj}} \end{pmatrix} \quad (4.30)$$

$$\Leftrightarrow \mathbf{C}_{\hat{\mathbf{w}}_{obj}} \Delta \hat{\mathbf{w}}_{obj} \geq \mathbf{d}_{\hat{\mathbf{w}}_{obj}} \quad (4.31)$$

$$\text{return } \mathbf{C}_{\hat{\mathbf{w}}_{obj}} := \begin{pmatrix} \mathbf{C}_{w_{obj},1} & & & \\ & \mathbf{C}_{w_{obj},2} & & \\ & & \ddots & \\ & & & \mathbf{C}_{w_{obj},N_{cnt-obj}} \end{pmatrix} \in \mathbb{R}^{N_{wrench-obj-ineq} \times 6N_{cnt-obj}}$$

:wrench-obj-inequality-constraint-vector *ℰkey (update? t)* [method]

$$\text{return } \mathbf{d}_{\hat{\mathbf{w}}_{obj}} := \begin{pmatrix} \mathbf{d}_{w_{obj},1} - \mathbf{C}_{w_{obj},1} \mathbf{w}_{obj,1} \\ \mathbf{d}_{w_{obj},2} - \mathbf{C}_{w_{obj},2} \mathbf{w}_{obj,2} \\ \vdots \\ \mathbf{d}_{w_{obj},N_{cnt-obj}} - \mathbf{C}_{w_{obj},N_{cnt-obj}} \mathbf{w}_{obj,N_{cnt-obj}} \end{pmatrix} \in \mathbb{R}^{N_{wrench-obj-ineq}}$$

:variant-config-inequality-constraint-matrix *ℰkey (update? nil)* [method]

$$\begin{cases} \mathbf{C}_\theta \Delta \boldsymbol{\theta} \geq \mathbf{d}_\theta \\ \mathbf{C}_{\hat{\mathbf{w}}} \Delta \hat{\mathbf{w}} \geq \mathbf{d}_{\hat{\mathbf{w}}} \\ \mathbf{C}_{\hat{\mathbf{w}}_{obj}} \Delta \hat{\mathbf{w}}_{obj} \geq \mathbf{d}_{\hat{\mathbf{w}}_{obj}} \\ \mathbf{C}_\tau \Delta \boldsymbol{\tau} \geq \mathbf{d}_\tau \end{cases} \quad (4.32)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{C}_\theta & & & \\ & \mathbf{C}_{\hat{\mathbf{w}}} & & \\ & & \mathbf{C}_{\hat{\mathbf{w}}_{obj}} & \\ & & & \mathbf{C}_\tau \end{pmatrix} \begin{pmatrix} \Delta \boldsymbol{\theta} \\ \Delta \hat{\mathbf{w}} \\ \Delta \hat{\mathbf{w}}_{obj} \\ \Delta \boldsymbol{\tau} \end{pmatrix} \geq \begin{pmatrix} \mathbf{d}_\theta \\ \mathbf{d}_{\hat{\mathbf{w}}} \\ \mathbf{d}_{\hat{\mathbf{w}}_{obj}} \\ \mathbf{d}_\tau \end{pmatrix} \quad (4.33)$$

$$\Leftrightarrow \mathbf{C}_{var} \Delta \mathbf{q}_{var} \geq \mathbf{d}_{var} \quad (4.34)$$

$$\text{return } \mathbf{C}_{var} := \begin{pmatrix} \mathbf{C}_\theta & & & \\ & \mathbf{C}_{\hat{\mathbf{w}}} & & \\ & & \mathbf{C}_{\hat{\mathbf{w}}_{obj}} & \\ & & & \mathbf{C}_\tau \end{pmatrix} \in \mathbb{R}^{N_{var-ineq} \times \dim(\mathbf{q}_{var})}$$

:variant-config-inequality-constraint-vector *ℓkey (update? t)* [method]

$$\text{return } \mathbf{d}_{var} := \begin{pmatrix} \mathbf{d}_\theta \\ \mathbf{d}_{\hat{\mathbf{w}}} \\ \mathbf{d}_{\hat{\mathbf{w}}_{obj}} \\ \mathbf{d}_\tau \end{pmatrix} \in \mathbb{R}^{N_{var-ineq}}$$

:act-react-equality-constraint-matrix *ℓkey (update? nil)* [method]

ロボット・物体間の接触レンチに関する作用・反作用の法則は次式のように表される．

$$\hat{\mathbf{w}}_{i(m)} + \hat{\mathbf{w}}_{obj,j(m)} = \mathbf{0} \quad (m = 1, 2, \dots, N_{act-react}) \quad (4.35)$$

$$\Leftrightarrow \mathbf{A}_{act-react,robot,m} \hat{\mathbf{w}} + \mathbf{A}_{act-react,obj,m} \hat{\mathbf{w}}_{obj} = \mathbf{0} \quad (m = 1, 2, \dots, N_{act-react}) \quad (4.36)$$

$$\text{where } \mathbf{A}_{act-react,robot,m} = \begin{pmatrix} \mathbf{O}_6 & \mathbf{O}_6 & \cdots & \mathbf{I}_6 & \cdots & \mathbf{O}_6 & \mathbf{O}_6 \end{pmatrix} \in \mathbb{R}^{6 \times 6N_{cnt}} \quad (4.37)$$

$$\mathbf{A}_{act-react,obj,m} = \begin{pmatrix} \mathbf{O}_6 & \mathbf{O}_6 & \cdots & \mathbf{I}_6 & \cdots & \mathbf{O}_6 & \mathbf{O}_6 \end{pmatrix} \in \mathbb{R}^{6 \times 6N_{cnt-obj}} \quad (4.38)$$

$$\Leftrightarrow \mathbf{A}_{act-react,robot} \hat{\mathbf{w}} + \mathbf{A}_{act-react,obj} \hat{\mathbf{w}}_{obj} = \mathbf{0} \quad (4.39)$$

$$\text{where } \mathbf{A}_{act-react,robot} = \begin{pmatrix} \mathbf{A}_{act-react,robot,1} \\ \vdots \\ \mathbf{A}_{act-react,robot,N_{act-react}} \end{pmatrix} \in \mathbb{R}^{6N_{act-react} \times 6N_{cnt}} \quad (4.40)$$

$$\mathbf{A}_{act-react,obj} = \begin{pmatrix} \mathbf{A}_{act-react,obj,1} \\ \vdots \\ \mathbf{A}_{act-react,obj,N_{act-react}} \end{pmatrix} \in \mathbb{R}^{6N_{act-react} \times 6N_{cnt-obj}} \quad (4.41)$$

$$\Leftrightarrow \mathbf{A}_{act-react} \begin{pmatrix} \hat{\mathbf{w}} \\ \hat{\mathbf{w}}_{obj} \end{pmatrix} = \mathbf{0} \in \mathbb{R}^{6N_{act-react}} \quad (4.42)$$

$$\text{where } \mathbf{A}_{act-react} = \begin{pmatrix} \mathbf{A}_{act-react,robot} & \mathbf{A}_{act-react,obj} \end{pmatrix} \in \mathbb{R}^{6N_{act-react} \times (6N_{cnt} + 6N_{cnt-obj})} \quad (4.43)$$

$$\Leftrightarrow \mathbf{A}_{act-react} \begin{pmatrix} \hat{\mathbf{w}} + \Delta \hat{\mathbf{w}} \\ \hat{\mathbf{w}}_{obj} + \Delta \hat{\mathbf{w}}_{obj} \end{pmatrix} = \mathbf{0} \quad (4.44)$$

$$\Leftrightarrow \mathbf{A}_{act-react} \begin{pmatrix} \Delta \hat{\mathbf{w}} \\ \Delta \hat{\mathbf{w}}_{obj} \end{pmatrix} = \mathbf{b}_{act-react} \quad (4.45)$$

$$\text{where } \mathbf{b}_{act-react} = -\mathbf{A}_{act-react} \begin{pmatrix} \hat{\mathbf{w}} \\ \hat{\mathbf{w}}_{obj} \end{pmatrix} \quad (4.46)$$

$i(m), j(m)$ は作用・反作用の関係にある接触レンチの m 番目の対におけるロボット，物体の接触レンチのインデックスである．

return $\mathbf{A}_{act-react} \in \mathbb{R}^{6N_{act-react} \times (6N_{cnt} + 6N_{cnt-obj})}$

:act-react-equality-constraint-vector $\mathcal{E}key$ (update? t) [method]

return $\mathbf{b}_{act-react} \in \mathbb{R}^{6N_{act-react}}$

:variant-config-equality-constraint-matrix $\mathcal{E}key$ (update? nil) [method]

$$\mathbf{A}_{act-react} \begin{pmatrix} \Delta \hat{\mathbf{w}} \\ \Delta \hat{\mathbf{w}}_{obj} \end{pmatrix} = \mathbf{b}_{act-react} \quad (4.47)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{O} & \mathbf{A}_{act-react} & \mathbf{O} \end{pmatrix} \begin{pmatrix} \Delta \boldsymbol{\theta} \\ \Delta \hat{\mathbf{w}} \\ \Delta \hat{\mathbf{w}}_{obj} \\ \Delta \boldsymbol{\tau} \end{pmatrix} = \mathbf{b}_{act-react} \quad (4.48)$$

$$\Leftrightarrow \mathbf{A}_{var} \Delta \mathbf{q}_{var} = \mathbf{b}_{var} \quad (4.49)$$

return $\mathbf{A}_{var} := \begin{pmatrix} \mathbf{O} & \mathbf{A}_{act-react} & \mathbf{O} \end{pmatrix} \in \mathbb{R}^{6N_{act-react} \times \dim(\mathbf{q}_{var})}$

:variant-config-equality-constraint-vector $\mathcal{E}key$ (*update?* t) [method]

return $\mathbf{b}_{var} := \mathbf{b}_{act-react} \in \mathbb{R}^{6N_{act-react}}$

:invariant-config-equality-constraint-matrix $\mathcal{E}key$ (*update?* nil) [method]

return $\mathbf{A}_{invar} \in \mathbb{R}^{0 \times \dim(\mathbf{q}_{invar})}$ (no equality constraint)

:invariant-config-equality-constraint-vector $\mathcal{E}key$ (*update?* t) [method]

return $\mathbf{b}_{invar} \in \mathbb{R}^0$ (no equality constraint)

:config-equality-constraint-matrix $\mathcal{E}key$ (*update?* nil) [method]

$$\mathbf{A}_{var} \Delta \mathbf{q}_{var} = \mathbf{b}_{var} \quad (4.50)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{A}_{var} & \mathbf{O} \end{pmatrix} \begin{pmatrix} \Delta \mathbf{q}_{var} \\ \Delta \mathbf{q}_{invar} \end{pmatrix} = \mathbf{b}_{var} \quad (4.51)$$

$$\Leftrightarrow \mathbf{A} \Delta \mathbf{q} = \mathbf{b} \quad (4.52)$$

return $\mathbf{A} := \begin{pmatrix} \mathbf{A}_{var} & \mathbf{O} \end{pmatrix} \in \mathbb{R}^{N_{eq} \times \dim(\mathbf{q})}$

:config-equality-constraint-vector $\mathcal{E}key$ (*update?* t) [method]

return $\mathbf{b} := \mathbf{b}_{var} \in \mathbb{R}^{N_{eq}}$

:torque-regular-matrix $\mathcal{E}key$ (*update?* nil) [method]

(*only-variant?* nil)

二次形式の正則化項として次式を考える .

$$F_{tau}(\mathbf{q}) = \left\| \frac{\boldsymbol{\tau}}{\boldsymbol{\tau}_{max}} \right\|^2 \quad (\text{ベクトルの要素ごとの割り算を表す}) \quad (4.53)$$

$$= \boldsymbol{\tau}^T \bar{\mathbf{W}}_{trq} \boldsymbol{\tau} \quad (4.54)$$

ここで ,

$$\bar{\mathbf{W}}_{trq} := \begin{pmatrix} \frac{1}{\tau_{max,1}^2} & & & \\ & \frac{1}{\tau_{max,2}^2} & & \\ & & \ddots & \\ & & & \frac{1}{\tau_{max,N_{drive-joint}}^2} \end{pmatrix} \in \mathbb{R}^{\dim(\boldsymbol{\tau}) \times \dim(\boldsymbol{\tau})} \quad (4.55)$$

only-variant? is true:

$$\mathbf{W}_{trq} := \begin{matrix} \dim(\boldsymbol{\theta}) \\ \dim(\hat{\mathbf{w}}) \\ \dim(\hat{\mathbf{w}}_{obj}) \\ \dim(\boldsymbol{\tau}) \end{matrix} \begin{pmatrix} \dim(\boldsymbol{\theta}) & \dim(\hat{\mathbf{w}}) & \dim(\hat{\mathbf{w}}_{obj}) & \dim(\boldsymbol{\tau}) \\ & & & \\ & & & \\ & & & \bar{\mathbf{W}}_{trq} \end{pmatrix} \in \mathbb{R}^{\dim(\mathbf{q}_{var}) \times \dim(\mathbf{q}_{var})} \quad (4.56)$$

otherwise:

$$\mathbf{W}_{trq} := \begin{matrix} \dim(\boldsymbol{\theta}) \\ \dim(\hat{\mathbf{w}}) \\ \dim(\hat{\mathbf{w}}_{obj}) \\ \dim(\boldsymbol{\tau}) \\ \dim(\boldsymbol{\phi}) \end{matrix} \begin{pmatrix} \dim(\boldsymbol{\theta}) & \dim(\hat{\mathbf{w}}) & \dim(\hat{\mathbf{w}}_{obj}) & \dim(\boldsymbol{\tau}) & \dim(\boldsymbol{\phi}) \\ & & & & \\ & & & & \\ & & & & \\ & & & \bar{\mathbf{W}}_{trq} & \end{pmatrix} \in \mathbb{R}^{\dim(\mathbf{q}) \times \dim(\mathbf{q})} \quad (4.57)$$

$$\bar{\mathbf{v}}_{trq} := \bar{\mathbf{W}}_{trq} \boldsymbol{\tau} \quad (4.58)$$

only-variant? is true:

$$\mathbf{v}_{trq} := \begin{pmatrix} 1 \\ \dim(\boldsymbol{\theta}) \\ \dim(\hat{\mathbf{w}}) \\ \dim(\hat{\mathbf{w}}_{obj}) \\ \dim(\boldsymbol{\tau}) \\ \bar{\mathbf{v}}_{trq} \end{pmatrix} \in \mathbb{R}^{\dim(\mathbf{q}_{var})} \quad (4.60)$$

otherwise:

$$\mathbf{v}_{trq} := \begin{pmatrix} 1 \\ \dim(\boldsymbol{\theta}) \\ \dim(\hat{\mathbf{w}}) \\ \dim(\hat{\mathbf{w}}_{obj}) \\ \dim(\boldsymbol{\tau}) \\ \dim(\boldsymbol{\phi}) \end{pmatrix} \in \mathbb{R}^{\dim(\mathbf{q})} \quad (4.61)$$

$$\text{return } \mathbf{v}_{trq}$$

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:collision-inequality-constraint-matrix key (update? nil) [method]
```

$$\mathbf{C}_{col} := N_{col} \begin{pmatrix} \dim(\boldsymbol{\theta}) & \dim(\hat{\mathbf{w}}) & \dim(\hat{\mathbf{w}}_{obj}) & \dim(\boldsymbol{\tau}) & \dim(\boldsymbol{\phi}) \\ \mathbf{C}_{col,\theta} & \mathbf{O} & \mathbf{O} & \mathbf{O} & \mathbf{C}_{col,\phi} \end{pmatrix} \quad (4.62)$$

return $\mathbf{C}_{col} \in \mathbb{R}^{N_{col} \times \dim(\mathbf{q})}$

:update-viewer	[method]
Update viewer.	

```
:print-status [method]
    Print status.
```

4.2 B スプラインを用いた関節軌道生成

4.2.1 B スプラインを用いた関節軌道生成の理論

一般の B スプライン基底関数の定義

B スプライン基底関数は以下で定義される .

$$b_{i,0}(t) \stackrel{\text{def}}{=} \begin{cases} 1 & \text{if } t_i \leq t < t_{i+1} \\ 0 & \text{otherwise} \end{cases} \quad (4.63)$$

$$b_{i,n}(t) \stackrel{\text{def}}{=} \frac{t - t_i}{t_{i+n} - t_i} b_{i,n-1}(t) + \frac{t_{i+n+1} - t}{t_{i+n+1} - t_{i+1}} b_{i+1,n-1}(t) \quad (4.64)$$

t_i はノットと呼ばれる .

使用区間を指定してノットを一様とする場合の B スプライン基底関数

t_s, t_f を B スプラインの使用区間の初期 , 終端時刻とする .

$n < m$ とする .

$$t_n = t_s \quad (4.65)$$

$$t_m = t_f \quad (4.66)$$

とする . t_i ($0 \leq i \leq n+m$) が等間隔に並ぶとすると ,

$$t_i = \frac{i-n}{m-n}(t_f - t_s) + t_s \quad (4.67)$$

$$= hi + \frac{mt_s - nt_f}{m-n} \quad (4.68)$$

ただし ,

$$h \stackrel{\text{def}}{=} \frac{t_f - t_s}{m-n} \quad (4.69)$$

式 (4.68) を式 (4.63) , 式 (4.64) に代入すると , B スプライン基底関数は次式で得られる .

$$b_{i,0}(t) = \begin{cases} 1 & \text{if } t_i \leq t < t_{i+1} \\ 0 & \text{otherwise} \end{cases} \quad (4.70)$$

$$b_{i,n}(t) = \frac{(t - t_i)b_{i,n-1}(t) + (t_{i+n+1} - t)b_{i+1,n-1}(t)}{nh} \quad (4.71)$$

以降では , n を B スプラインの次数 , m を制御点の個数と呼ぶ .

B スプラインの凸包性

式 (4.70) , 式 (4.71) で定義される B スプライン基底関数 $b_{i,n}(t)$ は次式のように凸包性を持つ .

$$\sum_{i=0}^{m-1} b_{i,n}(t) = 1 \quad (t_s \leq t \leq t_f) \quad (4.72)$$

$$0 \leq b_{i,n}(t) \leq 1 \quad (i = 0, 1, \dots, m-1, t_s \leq t \leq t_f) \quad (4.73)$$

B スプラインの微分

B スプライン基底関数の微分に関して次式が成り立つ¹¹ .

$$\dot{\mathbf{b}}_n(t) = \frac{d\mathbf{b}_n(t)}{dt} = \mathbf{D}\mathbf{b}_{n-1}(t) \quad (4.74)$$

ただし ,

$$\mathbf{b}_n(t) \stackrel{\text{def}}{=} \begin{pmatrix} b_{0,n}(t) \\ b_{1,n}(t) \\ \vdots \\ b_{m-1,n}(t) \end{pmatrix} \in \mathbb{R}^m \quad (4.75)$$

$$\mathbf{D} \stackrel{\text{def}}{=} \frac{1}{h} \begin{pmatrix} 1 & -1 & & & \mathbf{O} \\ & 1 & -1 & & \\ & & \ddots & \ddots & \\ & & & \ddots & -1 \\ \mathbf{O} & & & & 1 \end{pmatrix} \in \mathbb{R}^{m \times m} \quad (4.76)$$

したがって , k 階微分に関して次式が成り立つ .

$$\mathbf{b}_n^{(k)}(t) = \frac{d^{(k)}\mathbf{b}_n(t)}{dt^{(k)}} = \mathbf{D}^k \mathbf{b}_{n-k}(t) \quad (4.77)$$

B スプラインによる関節角軌道の表現

j 番目の関節角軌道 $\theta_j(t)$ を次式で表す .

$$\theta_j(t) \stackrel{\text{def}}{=} \sum_{i=0}^{m-1} p_{j,i} b_{i,n}(t) = \mathbf{p}_j^T \mathbf{b}_n(t) \in \mathbb{R} \quad (t_s \leq t \leq t_f) \quad (4.78)$$

ただし ,

$$\mathbf{p}_j = \begin{pmatrix} p_{j,0} \\ p_{j,1} \\ \vdots \\ p_{j,m-1} \end{pmatrix} \in \mathbb{R}^m, \quad \mathbf{b}_n(t) = \begin{pmatrix} b_{0,n}(t) \\ b_{1,n}(t) \\ \vdots \\ b_{m-1,n}(t) \end{pmatrix} \in \mathbb{R}^m \quad (4.79)$$

以降では , \mathbf{p}_j を制御点 , $\mathbf{b}_n(t)$ を基底関数と呼ぶ . 制御点 \mathbf{p}_j を決定すると関節角軌道が定まる . 制御点 \mathbf{p}_j を動作計画の設計変数とする .

$j = 1, 2, \dots, N_{\text{joint}}$ 番目の関節角軌道を並べたベクトル関数は ,

$$\boldsymbol{\theta}(t) \stackrel{\text{def}}{=} \begin{pmatrix} \theta_1(t) \\ \theta_2(t) \\ \vdots \\ \theta_{N_{\text{joint}}}(t) \end{pmatrix} = \begin{pmatrix} \mathbf{p}_1^T \mathbf{b}_n(t) \\ \mathbf{p}_2^T \mathbf{b}_n(t) \\ \vdots \\ \mathbf{p}_{N_{\text{joint}}}^T \mathbf{b}_n(t) \end{pmatrix} = \begin{pmatrix} \mathbf{p}_1^T \\ \mathbf{p}_2^T \\ \vdots \\ \mathbf{p}_{N_{\text{joint}}}^T \end{pmatrix} \mathbf{b}_n(t) = \mathbf{P} \mathbf{b}_n(t) \in \mathbb{R}^{N_{\text{joint}}} \quad (4.80)$$

ただし ,

$$\mathbf{P} \stackrel{\text{def}}{=} \begin{pmatrix} \mathbf{p}_1^T \\ \mathbf{p}_2^T \\ \vdots \\ \mathbf{p}_{N_{\text{joint}}}^T \end{pmatrix} \in \mathbb{R}^{N_{\text{joint}} \times m} \quad (4.81)$$

¹¹ 数学的帰納法で証明できる . <http://mat.fsv.cvut.cz/gcg/sbornik/prochazkova.pdf>

式 (4.80) は，制御点を縦に並べたベクトルとして分離して，以下のようにも表現できる．

$$\theta(t) = \begin{pmatrix} \theta_1(t) \\ \theta_2(t) \\ \vdots \\ \theta_{N_{joint}}(t) \end{pmatrix} = \begin{pmatrix} \mathbf{b}_n^T(t)\mathbf{p}_1 \\ \mathbf{b}_n^T(t)\mathbf{p}_2 \\ \vdots \\ \mathbf{b}_n^T(t)\mathbf{p}_{N_{joint}} \end{pmatrix} = \begin{pmatrix} \mathbf{b}_n^T(t) & & \mathbf{O} \\ & \mathbf{b}_n^T(t) & \\ & & \ddots \\ \mathbf{O} & & & \mathbf{b}_n^T(t) \end{pmatrix} \begin{pmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \\ \vdots \\ \mathbf{p}_{N_{joint}} \end{pmatrix} = \mathbf{B}_n(t)\mathbf{p} \in \mathbb{R}^{N_{joint}} \quad (4.82)$$

ただし，

$$\mathbf{B}_n(t) \stackrel{\text{def}}{=} \begin{pmatrix} \mathbf{b}_n^T(t) & & \mathbf{O} \\ & \mathbf{b}_n^T(t) & \\ & & \ddots \\ \mathbf{O} & & & \mathbf{b}_n^T(t) \end{pmatrix} \in \mathbb{R}^{N_{joint} \times mN_{joint}}, \quad \mathbf{p} \stackrel{\text{def}}{=} \begin{pmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \\ \vdots \\ \mathbf{p}_{N_{joint}} \end{pmatrix} \in \mathbb{R}^{mN_{joint}} \quad (4.83)$$

B スプラインによる関節角軌道の微分

式 (4.80) と式 (4.74) から，関節角速度軌道は次式で得られる．

$$\dot{\theta}(t) = \mathbf{P}\dot{\mathbf{b}}_n(t) \quad (4.84)$$

$$= \mathbf{P}\mathbf{D}\mathbf{b}_{n-1}(t) \quad (4.85)$$

$$= \begin{pmatrix} \mathbf{p}_1^T \\ \vdots \\ \mathbf{p}_{N_{joint}}^T \end{pmatrix} \mathbf{D}\mathbf{b}_{n-1}(t) \quad (4.86)$$

$$= \begin{pmatrix} \mathbf{p}_1^T \mathbf{D}\mathbf{b}_{n-1}(t) \\ \vdots \\ \mathbf{p}_{N_{joint}}^T \mathbf{D}\mathbf{b}_{n-1}(t) \end{pmatrix} \quad (4.87)$$

$$= \begin{pmatrix} \mathbf{b}_{n-1}^T(t) \mathbf{D}^T \mathbf{p}_1 \\ \vdots \\ \mathbf{b}_{n-1}^T(t) \mathbf{D}^T \mathbf{p}_{N_{joint}} \end{pmatrix} \quad (4.88)$$

$$= \begin{pmatrix} \mathbf{b}_{n-1}^T(t) \mathbf{D}^T & & \mathbf{O} \\ & \ddots & \\ \mathbf{O} & & \mathbf{b}_{n-1}^T(t) \mathbf{D}^T \end{pmatrix} \begin{pmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_{N_{joint}} \end{pmatrix} \quad (4.89)$$

$$= \begin{pmatrix} \mathbf{b}_{n-1}^T(t) & & \mathbf{O} \\ & \ddots & \\ \mathbf{O} & & \mathbf{b}_{n-1}^T(t) \end{pmatrix} \begin{pmatrix} \mathbf{D}^T & & \mathbf{O} \\ & \ddots & \\ \mathbf{O} & & \mathbf{D}^T \end{pmatrix} \begin{pmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_{N_{joint}} \end{pmatrix} \quad (4.90)$$

$$= \mathbf{B}_{n-1}(t) \hat{\mathbf{D}}_1 \mathbf{p} \quad (4.91)$$

ただし，

$$\hat{\mathbf{D}}_1 = \begin{pmatrix} \mathbf{D}^T & & \mathbf{O} \\ & \mathbf{D}^T & \\ & & \ddots \\ \mathbf{O} & & & \mathbf{D}^T \end{pmatrix} \in \mathbb{R}^{mN_{joint} \times mN_{joint}} \quad (4.92)$$

同様に、関節角軌道の k 階微分は次式で得られる。

$$\boldsymbol{\theta}^{(k)}(t) = \frac{d^{(k)}\boldsymbol{\theta}(t)}{dt^{(k)}} \quad (4.93)$$

$$= \boldsymbol{P}\boldsymbol{D}^k\boldsymbol{b}_{n-k}(t) \quad (4.94)$$

$$= \boldsymbol{B}_{n-k}(t)\hat{\boldsymbol{D}}_k\boldsymbol{p} \quad (4.95)$$

ただし、

$$\hat{\boldsymbol{D}}_k = \begin{pmatrix} (\boldsymbol{D}^k)^T & & \boldsymbol{O} \\ & \ddots & \\ \boldsymbol{O} & & (\boldsymbol{D}^k)^T \end{pmatrix} = (\hat{\boldsymbol{D}}_1)^k \in \mathbb{R}^{mN_{joint} \times mN_{joint}} \quad (4.96)$$

計算時間は式 (4.94) のほうが式 (4.95) より速い。

エンドエフェクタ位置姿勢拘束のタスク関数

関節角 $\boldsymbol{\theta} \in \mathbb{R}^{N_{joint}}$ からエンドエフェクタ位置姿勢 $\boldsymbol{r} \in \mathbb{R}^6$ への写像を $\boldsymbol{f}(\boldsymbol{\theta})$ で表す。

$$\boldsymbol{r} = \boldsymbol{f}(\boldsymbol{\theta}) \quad (4.97)$$

関節角軌道が式 (4.82) で表現されるとき、エンドエフェクタ軌道は次式で表される。

$$\boldsymbol{r}(t) = \boldsymbol{f}(\boldsymbol{\theta}(t)) = \boldsymbol{f}(\boldsymbol{B}_n(t)\boldsymbol{p}) \quad (4.98)$$

$l = 1, 2, \dots, N_{tm}$ について、時刻 t_l でエンドエフェクタの位置姿勢が \boldsymbol{r}_l であるタスクのタスク関数は次式で表される。以降では、 t_l をタイミングと呼ぶ。

$$\boldsymbol{e}(\boldsymbol{p}, \boldsymbol{t}) \stackrel{\text{def}}{=} \begin{pmatrix} \boldsymbol{e}_1(\boldsymbol{p}, t) \\ \boldsymbol{e}_2(\boldsymbol{p}, t) \\ \vdots \\ \boldsymbol{e}_{N_{tm}}(\boldsymbol{p}, t) \end{pmatrix} = \begin{pmatrix} \boldsymbol{r}_1 - \boldsymbol{f}(\boldsymbol{\theta}(t_1)) \\ \boldsymbol{r}_2 - \boldsymbol{f}(\boldsymbol{\theta}(t_2)) \\ \vdots \\ \boldsymbol{r}_{N_{tm}} - \boldsymbol{f}(\boldsymbol{\theta}(t_{N_{tm}})) \end{pmatrix} = \begin{pmatrix} \boldsymbol{r}_1 - \boldsymbol{f}(\boldsymbol{B}_n(t_1)\boldsymbol{p}) \\ \boldsymbol{r}_2 - \boldsymbol{f}(\boldsymbol{B}_n(t_2)\boldsymbol{p}) \\ \vdots \\ \boldsymbol{r}_{N_{tm}} - \boldsymbol{f}(\boldsymbol{B}_n(t_{N_{tm}})\boldsymbol{p}) \end{pmatrix} \in \mathbb{R}^{6N_{tm}} \quad (4.99)$$

ただし、

$$\boldsymbol{e}_l(\boldsymbol{p}, t) \stackrel{\text{def}}{=} \boldsymbol{r}_l - \boldsymbol{f}(\boldsymbol{\theta}(t_l)) = \boldsymbol{r}_l - \boldsymbol{f}(\boldsymbol{B}_n(t_l)\boldsymbol{p}) \in \mathbb{R}^6 \quad (l = 1, 2, \dots, N_{tm}) \quad (4.100)$$

$$\boldsymbol{t} \stackrel{\text{def}}{=} \begin{pmatrix} t_1 \\ t_2 \\ \vdots \\ t_{N_{tm}} \end{pmatrix} \in \mathbb{R}^{N_{tm}} \quad (4.101)$$

このタスクを実現する関節角軌道は、次の評価関数を最小にする制御点 \boldsymbol{p} 、タイミング \boldsymbol{t} を求めることで導出することができる。

$$F(\boldsymbol{p}, \boldsymbol{t}) \stackrel{\text{def}}{=} \frac{1}{2} \|\boldsymbol{e}(\boldsymbol{p}, \boldsymbol{t})\|^2 \quad (4.102)$$

$$= \frac{1}{2} \sum_{l=1}^{N_{tm}} \|\boldsymbol{r}_l - \boldsymbol{f}(\boldsymbol{\theta}(t_l))\|^2 \quad (4.103)$$

$$= \frac{1}{2} \sum_{l=1}^{N_{tm}} \|\boldsymbol{r}_l - \boldsymbol{f}(\boldsymbol{B}_n(t_l)\boldsymbol{p})\|^2 \quad (4.104)$$

また, l 番目の幾何拘束の許容誤差を $e_{tol,l} \geq 0 \in \mathbb{R}^6$ とする場合, タスク関数 $\tilde{e}_l(\mathbf{p}, t)$ は次式で表される.

$$\tilde{e}_{l,i}(\mathbf{p}, t) \stackrel{\text{def}}{=} \begin{cases} e_{l,i}(\mathbf{p}, t) - e_{tol,l,i} & e_{l,i}(\mathbf{p}, t) > e_{tol,l,i} \\ e_{l,i}(\mathbf{p}, t) + e_{tol,l,i} & e_{l,i}(\mathbf{p}, t) < -e_{tol,l,i} \\ 0 & \text{otherwise} \end{cases} \quad (i = 1, 2, \dots, 6) \quad (4.105)$$

$\tilde{e}_{l,i}(\mathbf{p}, t)$ は $\tilde{e}_l(\mathbf{p}, t)$ の i 番目の要素である. $e_{l,i}(\mathbf{p}, t)$ は $e(\mathbf{p}, t)$ の i 番目の要素である.

タスク関数を制御点で微分したヤコビ行列

式 (4.104) を目的関数とする最適化問題を Gauss-Newton 法, Levenberg-Marquardt 法や逐次二次計画法で解く場合, タスク関数 (4.99) のヤコビ行列が必要となる.

各時刻でのエンドエフェクタ位置姿勢拘束のタスク関数 $e_l(\mathbf{p}, t)$ の制御点 \mathbf{p} に対するヤコビ行列は次式で求められる.

$$\frac{\partial e_l(\mathbf{p}, t)}{\partial \mathbf{p}} = \frac{\partial}{\partial \mathbf{p}} \{ \mathbf{r}_l - \mathbf{f}(\mathbf{B}_n(t_l)\mathbf{p}) \} \quad (4.106)$$

$$= -\frac{\partial}{\partial \mathbf{p}} \mathbf{f}(\mathbf{B}_n(t_l)\mathbf{p}) \quad (4.107)$$

$$= -\left. \frac{\partial \mathbf{f}}{\partial \boldsymbol{\theta}} \right|_{\boldsymbol{\theta}=\boldsymbol{\theta}(t_l)} \frac{\partial \boldsymbol{\theta}}{\partial \mathbf{p}} \quad (4.108)$$

$$= -\mathbf{J}(\boldsymbol{\theta}(t_l)) \frac{\partial}{\partial \mathbf{p}} \{ \mathbf{B}_n(t_l)\mathbf{p} \} \quad (4.109)$$

$$= -\mathbf{J}(\boldsymbol{\theta}(t_l)) \mathbf{B}_n(t_l) \quad (4.110)$$

途中の変形で, $\boldsymbol{\theta}(\mathbf{p}; t) = \mathbf{B}_n(t)\mathbf{p}$ であることを利用した. ただし,

$$\mathbf{J} \stackrel{\text{def}}{=} \frac{\partial \mathbf{f}}{\partial \boldsymbol{\theta}} \quad (4.111)$$

タスク関数をタイミングで微分したヤコビ行列

各時刻でのエンドエフェクタ位置姿勢拘束のタスク関数 $e_l(\mathbf{p}, t)$ のタイミング t に対するヤコビ行列は次式で求められる.

$$\frac{\partial e_l(\mathbf{p}, t)}{\partial t_l} = \frac{\partial}{\partial t_l} \{ \mathbf{r}_l - \mathbf{f}(\mathbf{P}\mathbf{b}_n(t_l)) \} \quad (4.112)$$

$$= -\frac{\partial}{\partial t_l} \mathbf{f}(\mathbf{P}\mathbf{b}_n(t_l)) \quad (4.113)$$

$$= -\left. \frac{\partial \mathbf{f}}{\partial \boldsymbol{\theta}} \right|_{\boldsymbol{\theta}=\boldsymbol{\theta}(t_l)} \frac{\partial \boldsymbol{\theta}}{\partial t_l} \quad (4.114)$$

$$= -\mathbf{J}(\boldsymbol{\theta}(t_l)) \frac{\partial}{\partial t_l} \{ \mathbf{P}\mathbf{b}_n(t_l) \} \quad (4.115)$$

$$= -\mathbf{J}(\boldsymbol{\theta}(t_l)) \mathbf{P}\dot{\mathbf{b}}_n(t_l) \quad (4.116)$$

$$= -\mathbf{J}(\boldsymbol{\theta}(t_l)) \mathbf{P}\mathbf{D}\mathbf{b}_{n-1}(t_l) \quad (4.117)$$

途中の変形で, $\boldsymbol{\theta}(\mathbf{p}; t) = \mathbf{P}\mathbf{b}_n(t)$ であることを利用した.

初期・終端関節速度・加速度のタスク関数とヤコビ行列

初期，終端時刻の関節速度，加速度はゼロであるべきである．タスク関数は次式となる．

$$e_{sv}(\mathbf{p}, t) \stackrel{\text{def}}{=} \dot{\boldsymbol{\theta}}(t_s) \quad (4.118)$$

$$= \mathbf{B}_{n-1}(t_s) \hat{\mathbf{D}}_1 \mathbf{p} \quad (4.119)$$

$$= \mathbf{PD} \mathbf{b}_{n-1}(t_s) \quad (4.120)$$

$$e_{fv}(\mathbf{p}, t) \stackrel{\text{def}}{=} \dot{\boldsymbol{\theta}}(t_f) \quad (4.121)$$

$$= \mathbf{B}_{n-1}(t_f) \hat{\mathbf{D}}_1 \mathbf{p} \quad (4.122)$$

$$= \mathbf{PD} \mathbf{b}_{n-1}(t_f) \quad (4.123)$$

$$e_{sa}(\mathbf{p}, t) \stackrel{\text{def}}{=} \ddot{\boldsymbol{\theta}}(t_s) \quad (4.124)$$

$$= \mathbf{B}_{n-2}(t_s) \hat{\mathbf{D}}_2 \mathbf{p} \quad (4.125)$$

$$= \mathbf{PD}^2 \mathbf{b}_{n-2}(t_s) \quad (4.126)$$

$$e_{fa}(\mathbf{p}, t) \stackrel{\text{def}}{=} \ddot{\boldsymbol{\theta}}(t_f) \quad (4.127)$$

$$= \mathbf{B}_{n-2}(t_f) \hat{\mathbf{D}}_2 \mathbf{p} \quad (4.128)$$

$$= \mathbf{PD}^2 \mathbf{b}_{n-2}(t_f) \quad (4.129)$$

制御点で微分したヤコビ行列は次式で表される．

$$\frac{\partial e_{sv}(\mathbf{p}, t)}{\partial \mathbf{p}} = \mathbf{B}_{n-1}(t_s) \hat{\mathbf{D}}_1 \quad (4.130)$$

$$\frac{\partial e_{fv}(\mathbf{p}, t)}{\partial \mathbf{p}} = \mathbf{B}_{n-1}(t_f) \hat{\mathbf{D}}_1 \quad (4.131)$$

$$\frac{\partial e_{sa}(\mathbf{p}, t)}{\partial \mathbf{p}} = \mathbf{B}_{n-2}(t_s) \hat{\mathbf{D}}_2 \quad (4.132)$$

$$\frac{\partial e_{fa}(\mathbf{p}, t)}{\partial \mathbf{p}} = \mathbf{B}_{n-2}(t_f) \hat{\mathbf{D}}_2 \quad (4.133)$$

初期時刻，終端時刻で微分したヤコビ行列は次式で表される．

$$\frac{\partial e_{sv}(\mathbf{p}, t)}{\partial t_s} = \mathbf{PD} \frac{\partial \mathbf{b}_{n-1}(t_s)}{\partial t_s} = \mathbf{PD}^2 \mathbf{b}_{n-2}(t_s) \quad (4.134)$$

$$\frac{\partial e_{fv}(\mathbf{p}, t)}{\partial t_f} = \mathbf{PD} \frac{\partial \mathbf{b}_{n-1}(t_f)}{\partial t_f} = \mathbf{PD}^2 \mathbf{b}_{n-2}(t_f) \quad (4.135)$$

$$\frac{\partial e_{sa}(\mathbf{p}, t)}{\partial t_s} = \mathbf{PD}^2 \frac{\partial \mathbf{b}_{n-2}(t_s)}{\partial t_s} = \mathbf{PD}^3 \mathbf{b}_{n-3}(t_s) \quad (4.136)$$

$$\frac{\partial e_{fa}(\mathbf{p}, t)}{\partial t_f} = \mathbf{PD}^2 \frac{\partial \mathbf{b}_{n-2}(t_f)}{\partial t_f} = \mathbf{PD}^3 \mathbf{b}_{n-3}(t_f) \quad (4.137)$$

関節角上下限制約

式 (4.78) の関節角軌道定義において，

$$\mathbf{p}_j \leq \theta_{max,j} \mathbf{1}_m \quad (4.138)$$

のとき，B スプラインの凸包性 (式 (4.72)，式 (4.73)) より次式が成り立つ．ただし， $\mathbf{1}_m \in \mathbb{R}^m$ は全要素が 1

の m 次元ベクトルである .

$$\theta_j(t) = \sum_{i=0}^{m-1} p_{j,i} b_{i,n}(t) \quad (4.139)$$

$$\leq \sum_{i=0}^{m-1} \theta_{max,j} b_{i,n}(t) \quad (4.140)$$

$$= \theta_{max,j} \sum_{i=0}^{m-1} b_{i,n}(t) \quad (4.141)$$

$$= \theta_{max,j} \quad (4.142)$$

同様に , $\theta_{min,j} \mathbf{1}_m \leq \mathbf{p}_j$ とすれば , $\theta_{min,j} \leq \theta_j(t)$ が成り立つ .

したがって , j 番目の関節角の上下限を $\theta_{max,j}, \theta_{min,j}$ とすると , 次式の制約を制御点に課すことで , 関節角上下限制約を満たす関節角軌道が得られる .

$$\theta_{min,j} \mathbf{1}_m \leq \mathbf{p}_j \leq \theta_{max,j} \mathbf{1}_m \quad (j = 1, 2, \dots, N_{joint}) \quad (4.143)$$

つまり ,

$$\hat{\mathbf{E}} \boldsymbol{\theta}_{min} \leq \mathbf{p} \leq \hat{\mathbf{E}} \boldsymbol{\theta}_{max} \quad (4.144)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \mathbf{p} \geq \begin{pmatrix} \hat{\mathbf{E}} \boldsymbol{\theta}_{min} \\ -\hat{\mathbf{E}} \boldsymbol{\theta}_{max} \end{pmatrix} \quad (4.145)$$

ただし ,

$$\hat{\mathbf{E}} \stackrel{\text{def}}{=} \begin{pmatrix} \mathbf{1}_m & & \mathbf{0}_m \\ & \mathbf{1}_m & \\ & & \ddots \\ \mathbf{0}_m & & \mathbf{1}_m \end{pmatrix} \in \mathbb{R}^{m N_{joint} \times N_{joint}} \quad (4.146)$$

これは , 逐次二次計画法の中で , 次式の不等式制約となる .

$$\begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \Delta \mathbf{p} \geq \begin{pmatrix} \hat{\mathbf{E}} \boldsymbol{\theta}_{min} - \mathbf{p} \\ -\hat{\mathbf{E}} \boldsymbol{\theta}_{max} + \mathbf{p} \end{pmatrix} \quad (4.147)$$

関節角速度・角加速度上下限制約

式 (4.78) と式 (4.74) より , 関節角速度軌道 , 角加速度軌道は次式で表される .

$$\dot{\theta}_j(t) = \mathbf{p}_j^T \dot{\mathbf{b}}_n(t) = \mathbf{p}_j^T \mathbf{D} \mathbf{b}_{n-1}(t) = (\mathbf{D}^T \mathbf{p}_j)^T \mathbf{b}_{n-1}(t) \in \mathbb{R} \quad (t_s \leq t \leq t_f) \quad (4.148)$$

$$\ddot{\theta}_j(t) = \mathbf{p}_j^T \ddot{\mathbf{b}}_n(t) = \mathbf{p}_j^T \mathbf{D}^2 \mathbf{b}_{n-2}(t) = ((\mathbf{D}^2)^T \mathbf{p}_j)^T \mathbf{b}_{n-2}(t) \in \mathbb{R} \quad (t_s \leq t \leq t_f) \quad (4.149)$$

j 番目の関節角速度 , 角加速度の上限を $v_{max,j}, a_{max,j}$ とする . 関節角上下限制約の導出と同様に考えると , 次式の制約を制御点に課すことで , 関節角速度・角加速度上下限制約を満たす関節角軌道が得られる .

$$-v_{max,j} \mathbf{1}_m \leq \mathbf{D}^T \mathbf{p}_j \leq v_{max,j} \mathbf{1}_m \quad (j = 1, 2, \dots, N_{joint}) \quad (4.150)$$

$$-a_{max,j} \mathbf{1}_m \leq (\mathbf{D}^2)^T \mathbf{p}_j \leq a_{max,j} \mathbf{1}_m \quad (j = 1, 2, \dots, N_{joint}) \quad (4.151)$$

つまり,

$$-\hat{\mathbf{E}}\mathbf{v}_{max} \leq \hat{\mathbf{D}}_1\mathbf{p} \leq \hat{\mathbf{E}}\mathbf{v}_{max} \quad (4.152)$$

$$\Leftrightarrow \begin{pmatrix} \hat{\mathbf{D}}_1 \\ -\hat{\mathbf{D}}_1 \end{pmatrix} \mathbf{p} \geq \begin{pmatrix} -\hat{\mathbf{E}}\mathbf{v}_{max} \\ -\hat{\mathbf{E}}\mathbf{v}_{max} \end{pmatrix} \quad (4.153)$$

$$-\hat{\mathbf{E}}\mathbf{a}_{max} \leq \hat{\mathbf{D}}_2\mathbf{p} \leq \hat{\mathbf{E}}\mathbf{a}_{max} \quad (4.154)$$

$$\Leftrightarrow \begin{pmatrix} \hat{\mathbf{D}}_2 \\ -\hat{\mathbf{D}}_2 \end{pmatrix} \mathbf{p} \geq \begin{pmatrix} -\hat{\mathbf{E}}\mathbf{a}_{max} \\ -\hat{\mathbf{E}}\mathbf{a}_{max} \end{pmatrix} \quad (4.155)$$

これは, 逐次二次計画法の中で, 次式の不等式制約となる.

$$\begin{pmatrix} \hat{\mathbf{D}}_1 \\ -\hat{\mathbf{D}}_1 \end{pmatrix} \Delta\mathbf{p} \geq \begin{pmatrix} -\hat{\mathbf{E}}\mathbf{v}_{max} - \hat{\mathbf{D}}_1\mathbf{p} \\ -\hat{\mathbf{E}}\mathbf{v}_{max} + \hat{\mathbf{D}}_1\mathbf{p} \end{pmatrix} \quad (4.156)$$

$$\begin{pmatrix} \hat{\mathbf{D}}_2 \\ -\hat{\mathbf{D}}_2 \end{pmatrix} \Delta\mathbf{p} \geq \begin{pmatrix} -\hat{\mathbf{E}}\mathbf{a}_{max} - \hat{\mathbf{D}}_2\mathbf{p} \\ -\hat{\mathbf{E}}\mathbf{a}_{max} + \hat{\mathbf{D}}_2\mathbf{p} \end{pmatrix} \quad (4.157)$$

タイミング上下限制約

タイミングが初期, 終端時刻の間に含まれる制約は次式で表される.

$$t_s \leq t_l \leq t_f \quad (l = 1, 2, \dots, N_{tm}) \quad (4.158)$$

$$\Leftrightarrow t_s \mathbf{1} \leq \mathbf{t} \leq t_f \mathbf{1} \quad (4.159)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \mathbf{t} \geq \begin{pmatrix} t_s \mathbf{1} \\ -t_f \mathbf{1} \end{pmatrix} \quad (4.160)$$

これは, 逐次二次計画法の中で, 次式の不等式制約となる.

$$\begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \Delta\mathbf{t} \geq \begin{pmatrix} t_s \mathbf{1} - \mathbf{t} \\ -t_f \mathbf{1} + \mathbf{t} \end{pmatrix} \quad (4.161)$$

$$(4.162)$$

また, タイミングの順序が入れ替わることを許容しない場合, その制約は次式で表される.

$$t_l \leq t_{l+1} \quad (l = 1, 2, \dots, N_{tm} - 1) \quad (4.163)$$

$$\Leftrightarrow -t_l + t_{l+1} \geq 0 \quad (l = 1, 2, \dots, N_{tm} - 1) \quad (4.164)$$

$$\Leftrightarrow \mathbf{D}_{tm} \mathbf{t} \geq \mathbf{0} \quad (4.165)$$

ただし,

$$\mathbf{D}_{tm} = \begin{pmatrix} -1 & 1 & & & \mathbf{O} \\ & -1 & 1 & & \\ & & & \ddots & \\ \mathbf{O} & & & & -1 & 1 \end{pmatrix} \in \mathbb{R}^{(N_{tm}-1) \times N_{tm}} \quad (4.166)$$

これは, 逐次二次計画法の中で, 次式の不等式制約となる.

$$\mathbf{D}_{tm} \Delta\mathbf{t} \geq -\mathbf{D}_{tm} \mathbf{t} \quad (4.167)$$

関節角微分二乗積分最小化

関節角微分の二乗積分は次式で得られる．

$$F_{sqT,k}(\mathbf{p}) = \int_{t_s}^{t_f} \left\| \boldsymbol{\theta}^{(k)}(t) \right\|^2 dt \quad (4.168)$$

$$= \int_{t_s}^{t_f} \left\| \mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k \mathbf{p} \right\|^2 dt \quad (4.169)$$

$$= \int_{t_s}^{t_f} \left(\mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k \mathbf{p} \right)^T \left(\mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k \mathbf{p} \right) dt \quad (4.170)$$

$$= \mathbf{p}^T \left\{ \int_{t_s}^{t_f} \left(\mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k \right)^T \mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k dt \right\} \mathbf{p} \quad (4.171)$$

$$= \mathbf{p}^T \mathbf{H}_k \mathbf{p} \quad (4.172)$$

ただし，

$$\mathbf{H}_k = \int_{t_s}^{t_f} \left(\mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k \right)^T \mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k dt \quad (4.173)$$

$$\mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k = \begin{pmatrix} \mathbf{b}_{n-k}^T(t) & \mathbf{O} \\ & \ddots \\ \mathbf{O} & \mathbf{b}_{n-k}^T(t) \end{pmatrix} \begin{pmatrix} (\mathbf{D}^k)^T & \mathbf{O} \\ & \ddots \\ \mathbf{O} & (\mathbf{D}^k)^T \end{pmatrix} \quad (4.174)$$

$$= \begin{pmatrix} \mathbf{b}_{n-k}^T(t) (\mathbf{D}^k)^T & \mathbf{O} \\ & \ddots \\ \mathbf{O} & \mathbf{b}_{n-k}^T(t) (\mathbf{D}^k)^T \end{pmatrix} \quad (4.175)$$

$$= \begin{pmatrix} \left(\mathbf{D}^k \mathbf{b}_{n-k}(t) \right)^T & \mathbf{O} \\ & \ddots \\ \mathbf{O} & \left(\mathbf{D}^k \mathbf{b}_{n-k}(t) \right)^T \end{pmatrix} \quad (4.176)$$

$$\left(\mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k \right)^T \mathbf{B}_{n-k}(t) = \begin{pmatrix} \left(\mathbf{D}^k \mathbf{b}_{n-k}(t) \right)^T & \mathbf{O} \\ & \ddots \\ \mathbf{O} & \left(\mathbf{D}^k \mathbf{b}_{n-k}(t) \right)^T \end{pmatrix}^T \begin{pmatrix} \left(\mathbf{D}^k \mathbf{b}_{n-k}(t) \right)^T & \mathbf{O} \\ & \ddots \\ \mathbf{O} & \left(\mathbf{D}^k \mathbf{b}_{n-k}(t) \right)^T \end{pmatrix} \quad (4.177)$$

$$= \begin{pmatrix} \left(\mathbf{D}^k \mathbf{b}_{n-k}(t) \right) \left(\mathbf{D}^k \mathbf{b}_{n-k}(t) \right)^T & & \\ & \ddots & \\ \mathbf{O} & & \left(\mathbf{D}^k \mathbf{b}_{n-k}(t) \right) \left(\mathbf{D}^k \mathbf{b}_{n-k}(t) \right)^T \end{pmatrix} \quad (4.178)$$

これを逐次二次計画問題において，二次形式の正則化項として目的関数に加えることで，滑らかな動作が生成されることが期待される．

動作期間の最小化

動作期間 $(t_f - t_s)$ の二乗は次式で表される．

$$F_{duration}(\mathbf{t}) = |t_1 - t_{N_{tm}}|^2 \quad (4.179)$$

$$= \mathbf{t}^T \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} \mathbf{t} \quad (4.180)$$

ただし, 初期時刻 $t_s = t_1$, 終端時刻 $t_f = t_{N_{tm}}$ がタイミングベクトル t の最初, 最後の要素であるとする. これを逐次二次計画問題において, 二次形式の正則化項として目的関数に加えることで, 短時間でタスクを実現する動作が生成されることが期待される.

4.2.2 B スプラインを用いた関節軌道生成の実装

bspline-configuration-task

[class]

```

:super    propertied-object
:slots    (_robot robot instance)
           (_control-vector  $\mathbf{p}$ )
           (_timing-vector  $\mathbf{t}$ )
           (_num-kin  $N_{kin} := |\mathcal{T}^{kin-trg}| = |\mathcal{T}^{kin-att}|$ )
           (_num-joint  $N_{joint} := |\mathcal{J}|$ )
           (_num-control-point  $N_{ctrl}$ )
           (_num-timing  $N_{tm}$ )
           (_bspline-order B-spline order,  $n$ )
           (_dim-control-vector  $\dim(\mathbf{p})$ )
           (_dim-timing-vector  $\dim(\mathbf{t})$ )
           (_dim-config  $\dim(\mathbf{q})$ )
           (_dim-task  $\dim(\mathbf{e})$ )
           (_num-collision  $N_{col} :=$  number of collision check pairs)
           (_stationery-start-finish-task-scale  $k_{stat}$ )
           (_first-diff-square-integration-regular-scale  $k_{sqr,1}$ )
           (_second-diff-square-integration-regular-scale  $k_{sqr,2}$ )
           (_third-diff-square-integration-regular-scale  $k_{sqr,3}$ )
           (_motion-duration-regular-scale  $k_{duration}$ )
           (_norm-regular-scale-max  $k_{max,p}$ )
           (_norm-regular-scale-offset  $k_{off,p}$ )
           (_timing-norm-regular-scale-max  $k_{max,t}$ )
           (_timing-norm-regular-scale-offset  $k_{off,t}$ )
           (_joint-list  $\mathcal{J}$ )
           (_start-time  $t_s$ )
           (_finish-time  $t_f$ )
           (_kin-time-list  $\{t_1^{kin-tm}, t_2^{kin-tm}, \dots, t_{N_{kin}}^{kin-tm}\}$ )
           (_kin-variable-timing-list list of bool. t for variable timing.)
           (_kin-target-coords-list  $\mathcal{T}^{kin-trg}$ )
           (_kin-attention-coords-list  $\mathcal{T}^{kin-att}$ )
           (_kin-pos-tolerance-list list of position tolerance  $e_{tol,pos}$  [m])
           (_kin-rot-tolerance-list list of rotation tolerance  $e_{tol,rot}$  [rad])
           (_joint-angle-margin margin of  $\theta$  [deg] [mm])
           (_collision-pair-list list of bodyset-link or body pair)
           (_keep-timing-order? whether to keep order of timing  $\mathbf{t}$  or not)
           (_bspline-matrix buffer for  $\mathbf{B}_n(t)$ )

```

(_diff-mat buffer for D^k)
 (_diff-mat-list buffer for $\{D^1, D^2, \dots, D^K\}$)
 (_extended-diff-mat-list buffer for $\{\hat{D}_1, \hat{D}_2, \dots, \hat{D}_K\}$)
 (_task-jacobi buffer for $\frac{\partial e}{\partial q}$)
 (_regular-mat buffer for W_{reg})
 (_regular-vec buffer for v_{reg})

B スプラインを利用した軌道生成のためのコンフィギュレーション q とタスク関数 $e(q)$ のクラス .

コンフィギュレーション q の取得・更新, タスク関数 $e(q)$ の取得, タスク関数のヤコビ行列 $\frac{\partial e(q)}{\partial q}$ の取得, コンフィギュレーションの等式・不等式制約 A, b, C, d の取得のためのメソッドが定義されている .

コンフィギュレーション・タスク関数を定めるために, 初期化時に以下を与える

- ロボット

robot ロボットのインスタンス

joint-list \mathcal{J} 関節

- B スプラインのパラメータ

start-time t_s B スプラインの使用区間の初期時刻

finish-time t_f B スプラインの使用区間の終端時刻

num-control-point N_{ctrl} 制御点の個数

bspline-order n B スプラインの次数

- 幾何拘束

kin-target-coords-list $\mathcal{T}^{kin-try}$ 幾何到達目標位置姿勢リスト

kin-attention-coords-list $\mathcal{T}^{kin-att}$ 幾何到達着目位置姿勢リスト

kin-time-list $\{t_1^{kin-tm}, t_2^{kin-tm}, \dots, t_{N_{kin}}^{kin-tm}\}$ 幾何到達タイミングリスト

kin-variable-timing-list 幾何到達タイミングが可変か (t), 固定か (nil) のリスト . このリスト内の t の個数がタイミング t の次元 N_{tm} となる .

コンフィギュレーション q は以下から構成される .

$$q := \begin{pmatrix} p \\ t \end{pmatrix} \quad (4.181)$$

$p \in \mathbb{R}^{N_{ctrl}N_{joint}}$ 制御点 (B スプライン基底関数の山の高さ) [rad] [m]

$t \in \mathbb{R}^{N_{tm}}$ タイミング (幾何拘束タスクの課される時刻) [sec]

タスク関数 $e(q)$ は以下から構成される .

$$e(q) := \begin{pmatrix} e^{kin}(q) \\ e^{stat}(q) \end{pmatrix} \in \mathbb{R}^{6N_{kin}+4N_{joint}} \quad (4.182)$$

$e^{kin}(q) \in \mathbb{R}^{6N_{kin}}$ 幾何到達拘束 [rad] [m]

$e^{stat}(q) \in \mathbb{R}^{4N_{joint}}$ 初期, 終端時刻静止拘束 [rad][rad/s][rad/s²][m][m/s][m/s²]

:init \mathcal{E}_{key} (name)	[method]
(robot) (joint-list (send robot :joint-list)) (start-time 0.0) (finish-time 10.0) (num-control-point 10) (bspline-order 3) (kin-time-list) (kin-variable-timing-list (make-list (length kin-time-list) :initial-element nil)) (kin-target-coords-list) (kin-attention-coords-list) (kin-pos-tolerance-list (make-list (length kin-time-list) :initial-element 0.0)) (kin-rot-tolerance-list (make-list (length kin-time-list) :initial-element 0.0)) (joint-angle-margin 3.0) (collision-pair-list) (keep-timing-order? t) (stationery-start-finish-task-scale 0.0) (first-diff-square-integration-regular-scale 0.0) (second-diff-square-integration-regular-scale 0.0) (third-diff-square-integration-regular-scale 0.0) (motion-duration-regular-scale 0.0) (norm-regular-scale-max 1.000000e-05) (norm-regular-scale-offset 1.000000e-07) (timing-norm-regular-scale-max 1.000000e-05) (timing-norm-regular-scale-offset 1.000000e-07)	
Initialize instance	
:robot	[method]
return robot instance	
:joint-list	[method]
return \mathcal{J}	
:num-kin	[method]
return $N_{kin} := \mathcal{T}^{kin-trg} = \mathcal{T}^{kin-att} $	
:num-joint	[method]
return $N_{joint} := \mathcal{J} $	
:num-control-point	[method]
return N_{ctrl}	
:num-timing	[method]
return N_{tm}	
:num-collision	[method]
return $N_{col} :=$ number of collision check pairs	
:dim-config	[method]
return $dim(\mathbf{q}) := dim(\mathbf{p}) + dim(\mathbf{t}) = N_{ctrl}N_{joint} + N_{tm}$	

:dim-task [method]

return $\dim(\mathbf{e}) := \dim(\mathbf{e}^{kin}) + \dim(\mathbf{e}^{stat}) = 6N_{kin} + 4N_{joint}$

:control-vector [method]

return control vector \mathbf{p}

:timing-vector [method]

return timing vector \mathbf{t}

:config-vector [method]

return $\mathbf{q} := \begin{pmatrix} \mathbf{p} \\ \mathbf{t} \end{pmatrix}$

:set-control-vector *control-vector-new* *ℰkey* (*relative?* *nil*) [method]

Set \mathbf{p} .

:set-timing-vector *timing-vector-new* *ℰkey* (*relative?* *nil*) [method]

Set \mathbf{t} .

:set-config *config-new* *ℰkey* (*relative?* *nil*) [method]

Set \mathbf{q} .

:bspline-vector *tm* *ℰkey* (*order-offset* 0) [method]

$$\mathbf{b}_n(t) := \begin{pmatrix} b_{0,n}(t) \\ b_{1,n}(t) \\ \vdots \\ b_{N_{ctrl}-1,n}(t) \end{pmatrix} \in \mathbb{R}^{N_{ctrl}} \quad (4.183)$$

return $\mathbf{b}_n(t)$

:bspline-matrix *tm* *ℰkey* (*order-offset* 0) [method]

$$\mathbf{B}_n(t) := \begin{pmatrix} \mathbf{b}_n^T(t) & & & \mathbf{O} \\ & \mathbf{b}_n^T(t) & & \\ & & \ddots & \\ \mathbf{O} & & & \mathbf{b}_n^T(t) \end{pmatrix} \in \mathbb{R}^{N_{joint} \times N_{ctrl} N_{joint}} \quad (4.184)$$

return $\mathbf{B}_n(t)$

:differential-matrix *ℰkey* (*diff-order* 1) [method]

$$\mathbf{D} := \frac{1}{h} \begin{pmatrix} 1 & -1 & & & \mathbf{O} \\ & 1 & -1 & & \\ & & \ddots & \ddots & \\ & & & \ddots & -1 \\ \mathbf{O} & & & & 1 \end{pmatrix} \in \mathbb{R}^{N_{ctrl} \times N_{ctrl}} \quad (4.185)$$

return \mathbf{D}^k

:extended-differential-matrix *ℰkey (diff-order 1)*

[method]

$$\hat{\mathbf{D}}_k := \begin{pmatrix} (\mathbf{D}^k)^T & & \mathbf{O} \\ & \ddots & \\ \mathbf{O} & & (\mathbf{D}^k)^T \end{pmatrix} \in \mathbb{R}^{N_{ctrl} N_{joint} \times N_{ctrl} N_{joint}} \quad (4.186)$$

return $\hat{\mathbf{D}}_k$

:bspline-differential-matrix *tm ℰkey (diff-order 1)*

[method]

return $\mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k \in \mathbb{R}^{N_{joint} \times N_{ctrl} N_{joint}}$

:control-matrix

[method]

$$\mathbf{P} := \begin{pmatrix} \mathbf{p}_1^T \\ \mathbf{p}_2^T \\ \vdots \\ \mathbf{p}_{n_{joint}}^T \end{pmatrix} \in \mathbb{R}^{N_{joint} \times N_{ctrl}} \quad (4.187)$$

return \mathbf{P}

:theta *tm*

[method]

return $\boldsymbol{\theta}(t) = \mathbf{B}_n(t) \mathbf{p}$ [rad][m]

:theta-dot *tm ℰkey (diff-order 1)*

[method]

return $\boldsymbol{\theta}^{(k)}(t) = \frac{d^{(k)} \boldsymbol{\theta}(t)}{dt^{(k)}} = \mathbf{P} \mathbf{D}^k \mathbf{b}_{n-k}(t)$ [rad/s^k][m/s^k]

:theta-dot-numerical *tm ℰkey (diff-order 1)*

[method]

(delta-time 0.05)

return $\boldsymbol{\theta}^{(k)}(t) = \frac{d^{(k)} \boldsymbol{\theta}(t)}{dt^{(k)}} = \frac{\boldsymbol{\theta}^{(k-1)}(t + \Delta t) - \boldsymbol{\theta}^{(k-1)}(t)}{\Delta t}$ [rad/s^k][m/s^k]

:apply-theta-to-robot *tm*

[method]

apply $\boldsymbol{\theta}(t)$ to robot.

:kin-target-coords-list

[method]

$$\mathbf{T}_m^{kin-trg} = \{\mathbf{p}_l^{kin-trg}, \mathbf{R}_l^{kin-trg}\} \quad (l = 1, 2, \dots, N_{kin}) \quad (4.188)$$

return $\mathcal{T}^{kin-trg} := \{T_1^{kin-trg}, T_2^{kin-trg}, \dots, T_{N_{kin}}^{kin-trg}\}$

:kin-attention-coords-list

[method]

$$\mathbf{T}_m^{kin-att} = \{\mathbf{p}_l^{kin-att}, \mathbf{R}_l^{kin-att}\} \quad (l = 1, 2, \dots, N_{kin}) \quad (4.189)$$

return $\mathcal{T}^{kin-att} := \{T_1^{kin-att}, T_2^{kin-att}, \dots, T_{N_{kin}}^{kin-att}\}$

:kin-start-time

[method]

return $t_s^{kin} := t_1^{kin-tm}$

:kin-finish-time [method]

return $t_f^{kin} := t_{N_{kin}}^{kin-tm}$

:motion-duration [method]

return $(t_{N_{kin}}^{kin-tm} - t_1^{kin-tm})$

:kinematics-task-value \mathcal{E}_{key} (update? t) [method]

$$\mathbf{e}^{kin}(\mathbf{q}) = \mathbf{e}^{kin}(\mathbf{p}, t) \quad (4.190)$$

$$= \begin{pmatrix} \mathbf{e}_1^{kin}(\mathbf{p}, t) \\ \mathbf{e}_2^{kin}(\mathbf{p}, t) \\ \vdots \\ \mathbf{e}_{N_{kin}}^{kin}(\mathbf{p}, t) \end{pmatrix} \quad (4.191)$$

$$\mathbf{e}_l^{kin}(\mathbf{p}, t) = \begin{pmatrix} \mathbf{p}_l^{kin-trg} - \mathbf{p}_l^{kin-att}(\mathbf{p}, t) \\ a(\mathbf{R}_l^{kin-trg} \mathbf{R}_l^{kin-att}(\mathbf{p}, t)^T) \end{pmatrix} \in \mathbb{R}^6 \quad (l = 1, 2, \dots, N_{kin}) \quad (4.192)$$

$a(\mathbf{R})$ は姿勢行列 \mathbf{R} の等価角軸ベクトルを表す .

return $\mathbf{e}^{kin}(\mathbf{q}) \in \mathbb{R}^{6N_{kin}}$

:stationery-start-finish-task-value \mathcal{E}_{key} (update? t) [method]

$$\mathbf{e}^{stat}(\mathbf{q}) = \mathbf{e}^{stat}(\mathbf{p}, t) \quad (4.193)$$

$$= \begin{pmatrix} \mathbf{e}_{sv}^{stat}(\mathbf{p}, t) \\ \mathbf{e}_{fv}^{stat}(\mathbf{p}, t) \\ \mathbf{e}_{sa}^{stat}(\mathbf{p}, t) \\ \mathbf{e}_{fa}^{stat}(\mathbf{p}, t) \end{pmatrix} \quad (4.194)$$

$$\mathbf{e}_{sv}^{stat}(\mathbf{p}, t) := \dot{\boldsymbol{\theta}}(t_s^{kin}) \quad (4.195)$$

$$\mathbf{e}_{fv}^{stat}(\mathbf{p}, t) := \dot{\boldsymbol{\theta}}(t_f^{kin}) \quad (4.196)$$

$$\mathbf{e}_{sa}^{stat}(\mathbf{p}, t) := \ddot{\boldsymbol{\theta}}(t_s^{kin}) \quad (4.197)$$

$$\mathbf{e}_{fa}^{stat}(\mathbf{p}, t) := \ddot{\boldsymbol{\theta}}(t_f^{kin}) \quad (4.198)$$

return $\mathbf{e}^{stat}(\mathbf{q}) \in \mathbb{R}^{4N_{joint}}$

:task-value \mathcal{E}_{key} (update? t) [method]

return $\mathbf{e}(\mathbf{q}) := \begin{pmatrix} \mathbf{e}^{kin}(\mathbf{q}) \\ k_{stat} \mathbf{e}^{stat}(\mathbf{q}) \end{pmatrix} \in \mathbb{R}^{6N_{kin} + 4N_{joint}}$

:kinematics-task-jacobian-with-control-vector [method]

式 (4.110) より , タスク関数 \mathbf{e}^{kin} を制御点 \mathbf{p} で微分したヤコビ行列は次式で得られる .

$$\frac{\partial \mathbf{e}^{kin}}{\partial \mathbf{p}} = \begin{pmatrix} \frac{\partial \mathbf{e}_1^{kin}}{\partial \mathbf{p}} \\ \frac{\partial \mathbf{e}_2^{kin}}{\partial \mathbf{p}} \\ \vdots \\ \frac{\partial \mathbf{e}_{N_{kin}}^{kin}}{\partial \mathbf{p}} \end{pmatrix} \quad (4.199)$$

$$\frac{\partial \mathbf{e}_l^{kin}}{\partial \mathbf{p}} = -\mathbf{J}^{kin-att}(\boldsymbol{\theta}(t_l^{kin-tm})) \mathbf{B}_n(t_l^{kin-tm}) \quad (l = 1, 2, \dots, N_{kin}) \quad (4.200)$$

$$\text{return } \frac{\partial \mathbf{e}^{kin}}{\partial \mathbf{p}} \in \mathbb{R}^{6N_{kin} \times N_{ctrl}N_{joint}}$$

:kinematics-task-jacobian-with-timing-vector

[method]

式 (4.117) より , タスク関数 e^{kin} をタイミング t で微分したヤコビ行列は次式で得られる .

$$\frac{\partial \mathbf{e}^{kin}}{\partial \mathbf{t}} = \begin{pmatrix} \frac{\partial \mathbf{e}_1^{kin}}{\partial \mathbf{t}} \\ \frac{\partial \mathbf{e}_2^{kin}}{\partial \mathbf{t}} \\ \vdots \\ \frac{\partial \mathbf{e}_{N_{kin}}^{kin}}{\partial \mathbf{t}} \end{pmatrix} \quad (4.201)$$

$\frac{\partial \mathbf{e}_i^{kin}}{\partial \mathbf{t}}$ の i 番目の列ベクトル $\left[\frac{\partial \mathbf{e}_i^{kin}}{\partial \mathbf{t}} \right]_i \in \mathbb{R}^6$ は次式で表される ($i = 1, 2, \dots, N_{tm}$) .

$$\left[\frac{\partial \mathbf{e}_i^{kin}}{\partial \mathbf{t}} \right]_i = \begin{cases} -\mathbf{J}^{kin-att}(\boldsymbol{\theta}(t_l^{kin-tm})) \mathbf{P} \mathbf{D} \mathbf{b}_{n-1}(t_l^{kin-tm}) & t_l^{kin-tm} \text{ and } t_i \text{ is identical} \\ \mathbf{0} & \text{otherwise} \end{cases} \quad (4.202)$$

$$\text{return } \frac{\partial \mathbf{e}^{kin}}{\partial \mathbf{t}} \in \mathbb{R}^{6N_{kin} \times N_{tm}}$$

:stationery-start-finish-task-jacobian-with-control-vector

[method]

式 (4.130) , 式 (4.131) , 式 (4.132) , 式 (4.133) より , タスク関数 e^{stat} を制御点 \mathbf{p} で微分したヤコビ行列は次式で得られる .

$$\frac{\partial \mathbf{e}^{stat}}{\partial \mathbf{p}} = \begin{pmatrix} \frac{\partial \mathbf{e}_{sv}^{stat}}{\partial \mathbf{p}} \\ \frac{\partial \mathbf{e}_{fv}^{stat}}{\partial \mathbf{p}} \\ \frac{\partial \mathbf{e}_{sa}^{stat}}{\partial \mathbf{p}} \\ \frac{\partial \mathbf{e}_{fa}^{stat}}{\partial \mathbf{p}} \end{pmatrix} \quad (4.203)$$

$$\frac{\partial \mathbf{e}_{sv}^{stat}(\mathbf{p}, \mathbf{t})}{\partial \mathbf{p}} = \mathbf{B}_{n-1}(t_s^{kin}) \hat{\mathbf{D}}_1 \quad (4.204)$$

$$\frac{\partial \mathbf{e}_{fv}^{stat}(\mathbf{p}, \mathbf{t})}{\partial \mathbf{p}} = \mathbf{B}_{n-1}(t_f^{kin}) \hat{\mathbf{D}}_1 \quad (4.205)$$

$$\frac{\partial \mathbf{e}_{sa}^{stat}(\mathbf{p}, \mathbf{t})}{\partial \mathbf{p}} = \mathbf{B}_{n-2}(t_s^{kin}) \hat{\mathbf{D}}_2 \quad (4.206)$$

$$\frac{\partial \mathbf{e}_{fa}^{stat}(\mathbf{p}, \mathbf{t})}{\partial \mathbf{p}} = \mathbf{B}_{n-2}(t_f^{kin}) \hat{\mathbf{D}}_2 \quad (4.207)$$

$$\text{return } \frac{\partial \mathbf{e}^{stat}}{\partial \mathbf{p}} \in \mathbb{R}^{4N_{joint} \times N_{ctrl}N_{joint}}$$

:stationery-start-finish-task-jacobian-with-timing-vector

[method]

式 (4.134) , 式 (4.135) , 式 (4.136) , 式 (4.137) より , タスク関数 e^{stat} をタイミング t で微分したヤコビ行列は次式で得られる .

$$\frac{\partial \mathbf{e}^{stat}}{\partial \mathbf{t}} = \begin{pmatrix} \frac{\partial \mathbf{e}_{sv}^{stat}}{\partial \mathbf{t}} \\ \frac{\partial \mathbf{e}_{fv}^{stat}}{\partial \mathbf{t}} \\ \frac{\partial \mathbf{e}_{sa}^{stat}}{\partial \mathbf{t}} \\ \frac{\partial \mathbf{e}_{fa}^{stat}}{\partial \mathbf{t}} \end{pmatrix} \quad (4.208)$$

$\frac{\partial \mathbf{e}_x^{stat}}{\partial \mathbf{t}}$ の i 番目の列ベクトル $\left[\frac{\partial \mathbf{e}_x^{stat}}{\partial \mathbf{t}} \right]_i \in \mathbb{R}^{N_{joint}}$ は次式で表される ($x \in \{sv, fv, sa, fa\}, i = 1, 2, \dots, N_{tm}$) .

$$\left[\frac{\partial \mathbf{e}_{sv}^{stat}(\mathbf{p}, \mathbf{t})}{\partial \mathbf{t}} \right]_i = \begin{cases} PD^2 \mathbf{b}_{n-2}(t_s^{kin}) & t_s^{kin} \text{ and } t_i \text{ is identical} \\ \mathbf{0} & \text{otherwise} \end{cases} \quad (4.209)$$

$$\left[\frac{\partial \mathbf{e}_{fv}^{stat}(\mathbf{p}, \mathbf{t})}{\partial \mathbf{t}} \right]_i = \begin{cases} PD^2 \mathbf{b}_{n-2}(t_f^{kin}) & t_f^{kin} \text{ and } t_i \text{ is identical} \\ \mathbf{0} & \text{otherwise} \end{cases} \quad (4.210)$$

$$\left[\frac{\partial \mathbf{e}_{sa}^{stat}(\mathbf{p}, \mathbf{t})}{\partial \mathbf{t}} \right]_i = \begin{cases} PD^3 \mathbf{b}_{n-3}(t_s^{kin}) & t_s^{kin} \text{ and } t_i \text{ is identical} \\ \mathbf{0} & \text{otherwise} \end{cases} \quad (4.211)$$

$$\left[\frac{\partial \mathbf{e}_{fa}^{stat}(\mathbf{p}, \mathbf{t})}{\partial \mathbf{t}} \right]_i = \begin{cases} PD^3 \mathbf{b}_{n-3}(t_f^{kin}) & t_f^{kin} \text{ and } t_i \text{ is identical} \\ \mathbf{0} & \text{otherwise} \end{cases} \quad (4.212)$$

return $\frac{\partial \mathbf{e}^{stat}}{\partial \mathbf{t}} \in \mathbb{R}^{4N_{joint} \times N_{tm}}$

:task-jacobian

[method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}} = \begin{matrix} 6N_{kin} & N_{ctrl}N_{joint} & N_{tm} \\ 4N_{joint} & \begin{pmatrix} \frac{\partial \mathbf{e}^{kin}}{\partial \mathbf{p}} & \frac{\partial \mathbf{e}^{kin}}{\partial \mathbf{t}} \\ k_{stat} \frac{\partial \mathbf{e}^{stat}}{\partial \mathbf{p}} & k_{stat} \frac{\partial \mathbf{e}^{stat}}{\partial \mathbf{t}} \end{pmatrix} \end{matrix} \quad (4.213)$$

return $\frac{\partial \mathbf{e}}{\partial \mathbf{q}} = \mathbb{R}^{(6N_{kin} + 4N_{joint}) \times (N_{ctrl}N_{joint} + N_{tm})}$

:theta-max-vector \mathcal{E}_{key} (update? nil)

[method]

return $\boldsymbol{\theta}_{max} \in \mathbb{R}^{N_{joint}}$

:theta-min-vector \mathcal{E}_{key} (update? nil)

[method]

return $\boldsymbol{\theta}_{min} \in \mathbb{R}^{N_{joint}}$

:theta-inequality-constraint-matrix \mathcal{E}_{key} (update? nil)

[method]

式 (4.144) より , 関節角度上下制限約は次式で表される .

$$\hat{\mathbf{E}}\boldsymbol{\theta}_{min} \leq \mathbf{p} + \Delta\mathbf{p} \leq \hat{\mathbf{E}}\boldsymbol{\theta}_{max} \quad (4.214)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \Delta\mathbf{p} \geq \begin{pmatrix} \hat{\mathbf{E}}\boldsymbol{\theta}_{min} - \mathbf{p} \\ -\hat{\mathbf{E}}\boldsymbol{\theta}_{max} + \mathbf{p} \end{pmatrix} \quad (4.215)$$

$$\Leftrightarrow \mathbf{C}_\theta \Delta\mathbf{p} \geq \mathbf{d}_\theta \quad (4.216)$$

ただし ,

$$\hat{\mathbf{E}} := \begin{pmatrix} \mathbf{1}_{N_{ctrl}} & & \mathbf{0}_{N_{ctrl}} \\ & \mathbf{1}_{N_{ctrl}} & \\ & & \ddots \\ \mathbf{0}_{N_{ctrl}} & & \mathbf{1}_{N_{ctrl}} \end{pmatrix} \in \mathbb{R}^{N_{ctrl}N_{joint} \times N_{joint}} \quad (4.217)$$

$\mathbf{1}_{N_{ctrl}} \in \mathbb{R}^{N_{ctrl}}$ は全要素が 1 の N_{ctrl} 次元ベクトルである .

return $\mathbf{C}_\theta := \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \in \mathbb{R}^{2N_{ctrl}N_{joint} \times N_{ctrl}N_{joint}}$

:theta-inequality-constraint-vector \mathcal{E}_{key} (update? t)

[method]

return $\mathbf{d}_\theta := \begin{pmatrix} \hat{\mathbf{E}}\boldsymbol{\theta}_{min} - \mathbf{p} \\ -\hat{\mathbf{E}}\boldsymbol{\theta}_{max} + \mathbf{p} \end{pmatrix} \in \mathbb{R}^{2N_{ctrl}N_{joint}}$

:velocity-max-vector $\mathcal{E}key$ (*update?* *nil*) [method]
 return $\mathbf{v}_{max} \in \mathbb{R}^{N_{joint}}$

:velocity-inequality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]
 式 (4.152) より , 関節速度上下限制約は次式で表される .

$$-\hat{\mathbf{E}}\mathbf{v}_{max} \leq \hat{\mathbf{D}}_1(\mathbf{p} + \Delta\mathbf{p}) \leq \hat{\mathbf{E}}\mathbf{v}_{max} \quad (4.218)$$

$$\Leftrightarrow \begin{pmatrix} \hat{\mathbf{D}}_1 \\ -\hat{\mathbf{D}}_1 \end{pmatrix} \Delta\mathbf{p} \geq \begin{pmatrix} -\hat{\mathbf{E}}\mathbf{v}_{max} - \hat{\mathbf{D}}_1\mathbf{p} \\ -\hat{\mathbf{E}}\mathbf{v}_{max} + \hat{\mathbf{D}}_1\mathbf{p} \end{pmatrix} \quad (4.219)$$

$$\Leftrightarrow \mathbf{C}_{\dot{\theta}}\Delta\mathbf{p} \geq \mathbf{d}_{\dot{\theta}} \quad (4.220)$$

$$\text{return } \mathbf{C}_{\dot{\theta}} := \begin{pmatrix} \hat{\mathbf{D}}_1 \\ -\hat{\mathbf{D}}_1 \end{pmatrix} \in \mathbb{R}^{2N_{ctrl}N_{joint} \times N_{ctrl}N_{joint}}$$

:velocity-inequality-constraint-vector $\mathcal{E}key$ (*update?* *t*) [method]

$$\text{return } \mathbf{d}_{\dot{\theta}} := \begin{pmatrix} -\hat{\mathbf{E}}\mathbf{v}_{max} - \hat{\mathbf{D}}_1\mathbf{p} \\ -\hat{\mathbf{E}}\mathbf{v}_{max} + \hat{\mathbf{D}}_1\mathbf{p} \end{pmatrix} \in \mathbb{R}^{2N_{ctrl}N_{joint}}$$

:acceleration-max-vector $\mathcal{E}key$ (*update?* *nil*) [method]

$$\text{return } \mathbf{a}_{max} \in \mathbb{R}^{N_{joint}}$$

:acceleration-inequality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]

式 (4.154) より , 関節加速度上下限制約は次式で表される .

$$-\hat{\mathbf{E}}\mathbf{a}_{max} \leq \hat{\mathbf{D}}_2(\mathbf{p} + \Delta\mathbf{p}) \leq \hat{\mathbf{E}}\mathbf{a}_{max} \quad (4.221)$$

$$\Leftrightarrow \begin{pmatrix} \hat{\mathbf{D}}_2 \\ -\hat{\mathbf{D}}_2 \end{pmatrix} \Delta\mathbf{p} \geq \begin{pmatrix} -\hat{\mathbf{E}}\mathbf{a}_{max} - \hat{\mathbf{D}}_2\mathbf{p} \\ -\hat{\mathbf{E}}\mathbf{a}_{max} + \hat{\mathbf{D}}_2\mathbf{p} \end{pmatrix} \quad (4.222)$$

$$\Leftrightarrow \mathbf{C}_{\ddot{\theta}}\Delta\mathbf{p} \geq \mathbf{d}_{\ddot{\theta}} \quad (4.223)$$

$$\text{return } \mathbf{C}_{\ddot{\theta}} := \begin{pmatrix} \hat{\mathbf{D}}_2 \\ -\hat{\mathbf{D}}_2 \end{pmatrix} \in \mathbb{R}^{2N_{ctrl}N_{joint} \times N_{ctrl}N_{joint}}$$

:acceleration-inequality-constraint-vector $\mathcal{E}key$ (*update?* *t*) [method]

$$\text{return } \mathbf{d}_{\ddot{\theta}} := \begin{pmatrix} -\hat{\mathbf{E}}\mathbf{a}_{max} - \hat{\mathbf{D}}_2\mathbf{p} \\ -\hat{\mathbf{E}}\mathbf{a}_{max} + \hat{\mathbf{D}}_2\mathbf{p} \end{pmatrix} \in \mathbb{R}^{2N_{ctrl}N_{joint}}$$

:control-vector-inequality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]

$$\begin{cases} \mathbf{C}_{\theta}\Delta\mathbf{p} \geq \mathbf{d}_{\theta} \\ \mathbf{C}_{\dot{\theta}}\Delta\mathbf{p} \geq \mathbf{d}_{\dot{\theta}} \\ \mathbf{C}_{\ddot{\theta}}\Delta\mathbf{p} \geq \mathbf{d}_{\ddot{\theta}} \end{cases} \quad (4.224)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{C}_{\theta} \\ \mathbf{C}_{\dot{\theta}} \\ \mathbf{C}_{\ddot{\theta}} \end{pmatrix} \Delta\mathbf{p} \geq \begin{pmatrix} \mathbf{d}_{\theta} \\ \mathbf{d}_{\dot{\theta}} \\ \mathbf{d}_{\ddot{\theta}} \end{pmatrix} \quad (4.225)$$

$$\Leftrightarrow \mathbf{C}_p\Delta\mathbf{p} \geq \mathbf{d}_p \quad (4.226)$$

$$\text{return } \mathbf{C}_p := \begin{pmatrix} \mathbf{C}_{\theta} \\ \mathbf{C}_{\dot{\theta}} \\ \mathbf{C}_{\ddot{\theta}} \end{pmatrix} \in \mathbb{R}^{N_{p-ineq} \times \dim(\mathbf{p})}$$

:control-vector-inequality-constraint-vector $\mathcal{E}key$ (*update?* *t*) [method]

$$\text{return } \mathbf{d}_p := \begin{pmatrix} \mathbf{d}_\theta \\ \mathbf{d}_{\dot{\theta}} \\ \mathbf{d}_{\ddot{\theta}} \end{pmatrix} \in \mathbb{R}^{N_{p-ineq}}$$

:timing-vector-inequality-constraint-matrix $\mathcal{E}_{key} \text{ (update? nil)}$ [method]

式 (4.159) より，タイミングが B スプラインの初期，終端時刻の間に含まれる制約は次式で表される．

$$t_s \mathbf{1} \leq \mathbf{t} + \Delta \mathbf{t} \leq t_f \mathbf{1} \quad (4.227)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \Delta \mathbf{t} \geq \begin{pmatrix} t_s \mathbf{1} - \mathbf{t} \\ -t_f \mathbf{1} + \mathbf{t} \end{pmatrix} \quad (4.228)$$

また，式 (4.165) より，タイミングの順序が入れ替わることを許容しない場合，その制約は次式で表される．

$$\mathbf{D}_{tm}(\mathbf{t} + \Delta \mathbf{t}) \geq \mathbf{0} \quad (4.229)$$

$$\Leftrightarrow \mathbf{D}_{tm} \Delta \mathbf{t} \geq -\mathbf{D}_{tm} \mathbf{t} \quad (4.230)$$

ただし，

$$\mathbf{D}_{tm} = \begin{pmatrix} -1 & 1 & & & \mathbf{O} \\ & -1 & 1 & & \\ & & & \ddots & \\ \mathbf{O} & & & & -1 & 1 \end{pmatrix} \in \mathbb{R}^{(N_{tm}-1) \times N_{tm}} \quad (4.231)$$

これらを合わせると，

$$\begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \\ \mathbf{D}_{tm} \end{pmatrix} \Delta \mathbf{t} \geq \begin{pmatrix} t_s \mathbf{1} - \mathbf{t} \\ -t_f \mathbf{1} + \mathbf{t} \\ -\mathbf{D}_{tm} \mathbf{t} \end{pmatrix} \Leftrightarrow \mathbf{C}_t \Delta \mathbf{p} \geq \mathbf{d}_t \quad (4.232)$$

$$\text{return } \mathbf{C}_t := \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \\ \mathbf{D}_{tm} \end{pmatrix} \in \mathbb{R}^{(3N_{tm}-1) \times \dim(\mathbf{t})}$$

:timing-vector-inequality-constraint-vector $\mathcal{E}_{key} \text{ (update? t)}$ [method]

$$\text{return } \mathbf{d}_t := \begin{pmatrix} t_s \mathbf{1} - \mathbf{t} \\ -t_f \mathbf{1} + \mathbf{t} \\ -\mathbf{D}_{tm} \mathbf{t} \end{pmatrix} \in \mathbb{R}^{(3N_{tm}-1)}$$

:config-inequality-constraint-matrix $\mathcal{E}_{key} \text{ (update? nil)}$ [method]
(update-collision? nil)

$$\begin{cases} \mathbf{C}_p \Delta \mathbf{p} \geq \mathbf{d}_p \\ \mathbf{C}_t \Delta \mathbf{t} \geq \mathbf{d}_t \end{cases} \quad (4.233)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{C}_p & \mathbf{C}_t \end{pmatrix} \begin{pmatrix} \Delta \mathbf{p} \\ \Delta \mathbf{t} \end{pmatrix} \geq \begin{pmatrix} \mathbf{d}_p \\ \mathbf{d}_t \end{pmatrix} \quad (4.234)$$

$$\Leftrightarrow \mathbf{C} \Delta \mathbf{q} \geq \mathbf{d} \quad (4.235)$$

$$\text{return } \mathbf{C} := \begin{pmatrix} \mathbf{C}_p \\ \mathbf{C}_t \end{pmatrix} \in \mathbb{R}^{N_{ineq} \times \dim(\mathbf{q})}$$

```
:config-inequality-constraint-vector Ekey (update? t) [method]
(update-collision? nil)
```

$$\text{return } \mathbf{d} := \begin{pmatrix} \mathbf{d}_p \\ \mathbf{d}_t \end{pmatrix} \in \mathbb{R}^{N_{ineq}}$$

```

:config-equality-constraint-matrix  $\mathcal{E}_{key}$  (update? nil) [method]
  return  $\mathbf{A} \in \mathbb{R}^{0 \times \dim(\mathbf{q})}$  (no equality constraint)

```

```

:config-equality-constraint-vector  $\mathcal{E}_{key}$  (update?  $t$ ) [method]
  return  $\mathbf{b} \in \mathbb{R}^0$  (no equality constraint)

```

```

:square-integration-regular-matrix key (diff-order 1) [method]
                                   (delta-time (/ (- finish-time start-time) 100.0))

```

式 (4.172) より，関節角微分の二乗積分は次式で得られる．

$$F_{sq,r,k}(\mathbf{p}) = \int_{t_i}^{t_f} \left\| \boldsymbol{\theta}^{(k)}(t) \right\|^2 dt \quad (4.236)$$

$$= \mathbf{p}^T \mathbf{H}_{sgt,k} \mathbf{p} \quad (4.237)$$

ただし、

$$\mathbf{H}_{sq,r,k} = \int_{t_-}^{t_f} \left(\mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k \right)^T \mathbf{B}_{n-k}(t) \hat{\mathbf{D}}_k dt \quad (4.238)$$

$$= \int_{t_s}^{t_f} \begin{pmatrix} (D^k \mathbf{b}_{n-k}(t)) (D^k \mathbf{b}_{n-k}(t))^T & & \mathbf{O} \\ & \ddots & \\ \mathbf{O} & & (D^k \mathbf{b}_{n-k}(t)) (D^k \mathbf{b}_{n-k}(t))^T \end{pmatrix} dt \quad (4.239)$$

これは二次形式の正則化項である.

return $\mathbf{H}_{sgr,k} \in \mathbb{R}^{dim(\mathbf{p}) \times dim(\mathbf{p})}$

```

:first-differential-square-integration-regular-matrix  &key (delta-time (/ (- finish-time start-time)
100.0))

```

return $\mathbf{H}_{sqr-1} \in \mathbb{R}^{dim(\mathbf{p}) \times dim(\mathbf{p})}$

```

:second-differential-square-integration-regular-matrix key (delta-time (/ (- finish-time start-time)
100.0))

```

return $\mathbf{H}_{sqr.2} \in \mathbb{R}^{dim(\mathbf{p}) \times dim(\mathbf{p})}$

```

:third-differential-square-integration-regular-matrix $key (delta-time (/ (- _finish-time _start-time)
100.0))
[method]

```

```

return  $\mathbf{H}_{sqr.3} \in \mathbb{R}^{dim(\mathbf{p}) \times dim(\mathbf{p})}$ 

```

```
:control-vector-regular-matrix [method]
```

$$\mathbf{W}_{req,p} := \min(k_{max,p}, \|e\|^2 + k_{off,p})\mathbf{I} + k_{sqr,1}\mathbf{H}_{sqr,1} + k_{sqr,2}\mathbf{H}_{sqr,2} + k_{sqr,3}\mathbf{H}_{sqr,3} \quad (4.240)$$

return $\mathbf{W}_{req,p} \in \mathbb{R}^{dim(\mathbf{p}) \times dim(\mathbf{p})}$

```
:control-vector-regular-vector [method]
```

$$\mathbf{v}_{reg,p} := (k_{sqr,1} \mathbf{H}_{sqr,1} + k_{sqr,2} \mathbf{H}_{sqr,2} + k_{sqr,3} \mathbf{H}_{sqr,3}) \mathbf{p} \quad (4.241)$$

return $\mathbf{v}_{reg,p} \in \mathbb{R}^{dim(\mathbf{p})}$

:motion-duration-regular-matrix

[method]

式 (4.180) より , 動作期間の二乗は次式で得られる .

$$F_{duration}(\mathbf{t}) = |t_1 - t_{N_{tm}}|^2 \quad (4.242)$$

$$= \mathbf{t}^T \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} \mathbf{t} \quad (4.243)$$

$$= \mathbf{t}^T \mathbf{H}_{duration} \mathbf{t} \quad (4.244)$$

これは二次形式の正則化項である .

return $\mathbf{H}_{duration} \in \mathbb{R}^{dim(\mathbf{t}) \times dim(\mathbf{t})}$

:timing-vector-regular-matrix

[method]

$$\mathbf{W}_{reg,t} := \min(k_{max,t}, \|\mathbf{e}\|^2 + k_{off,t}) \mathbf{I} + k_{duration} \mathbf{H}_{duration} \quad (4.245)$$

return $\mathbf{W}_{reg,t} \in \mathbb{R}^{dim(\mathbf{t}) \times dim(\mathbf{t})}$

:timing-vector-regular-vector

[method]

$$\mathbf{v}_{reg,t} := k_{duration} \mathbf{H}_{duration} \mathbf{t} \quad (4.246)$$

return $\mathbf{v}_{reg,t} \in \mathbb{R}^{dim(\mathbf{t})}$

:regular-matrix

[method]

$$\mathbf{W}_{reg} := \begin{pmatrix} \mathbf{W}_{reg,p} & \\ & \mathbf{W}_{reg,t} \end{pmatrix} \quad (4.247)$$

return $\mathbf{W}_{reg} \in \mathbb{R}^{dim(\mathbf{q}) \times dim(\mathbf{q})}$

:regular-vector

[method]

$$\mathbf{v}_{reg} := \begin{pmatrix} \mathbf{v}_{reg,p} \\ \mathbf{v}_{reg,t} \end{pmatrix} \quad (4.248)$$

return $\mathbf{v}_{reg} \in \mathbb{R}^{dim(\mathbf{q}) \times dim(\mathbf{q})}$

:update-collision-inequality-constraint

[method]

Not implemented yet.

:update-viewer *key (trajectory-delta-time (/ (- _finish-time _start-time) 10.0))*

[method]

Update viewer.

:print-status [method]

Print status.

:print-motion-information [method]

Print motion information.

:play-animation $\mathcal{E}key$ (*robot*) [method]

(*delta-time* (/ (- *finish-time* *start-time*) 100.0))

(*only-motion-duration?* *t*)

(*loop?* *t*)

(*visualize-callback-func*)

Play motion animation.

:plot-theta-graph $\mathcal{E}key$ (*joint-id* *nil*) [method]

(*divide-num* 200)

(*plot-numerical?* *nil*)

(*only-motion-duration?* *t*)

(*dat-filename* /tmp/bspline-configuration-task-plot-theta-graph.dat)

(*dump-pdf?* *nil*)

(*dump-filename* (ros::resolve-ros-path package://eus_qp/optmotiongen/logs/bspline-configuration-task-plot-theta-graph.pdf))

Plot graph.

:generate-angle-vector-sequence $\mathcal{E}key$ (*divide-num* 100) [method]

(*start-time* (send self :kin-start-time))

(*finish-time* (send self :kin-finish-time))

(*delta-time* (/ (float (- *finish-time* *start-time*)) *divide-num*))

Generate angle-vector-sequence.

get-bspline-knot *i n x_min x_max h* [function]

$$t_i = \frac{i-n}{m-n}(t_f - t_s) + t_s \quad (4.249)$$

$$= hi + \frac{mt_s - nt_f}{m-n} \quad (4.250)$$

return knot t_i for B-spline function

bspline-basis-func *x i n m x_min x_max* $\mathcal{E}optional$ (*n-orig* *n*) (*m-orig* *m*) [function]

$$b_{i,0}(t) = \begin{cases} 1 & \text{if } t_i \leq t < t_{i+1} \\ 0 & \text{otherwise} \end{cases} \quad (4.251)$$

$$b_{i,n}(t) = \frac{(t - t_i)b_{i,n-1}(t) + (t_{i+n+1} - t)b_{i+1,n-1}(t)}{nh} \quad (4.252)$$

return B-spline function value $b_{i,n}(t)$.

4.3 B スプラインを用いた動的動作の生成

bspline-trajectory [class]

```

:super    propertied-object
:slots    (_start-time  $t_s$ )
           (_finish-time  $t_f$ )
           (_num-control-point  $N_{ctrl}$ )
           (_bspline-order B-spline order,  $n$ )
           (_dim-instant-config  $N_{\bar{q}}$ )
           (_dim-control-vector  $dim(\mathbf{p}) := N_{ctrl}N_{\bar{q}}$ )
           (_control-vector  $\mathbf{p}$ )
           (_zero-diff-stationery-start-finish-regular-scale  $k_{stat,0}$ )
           (_first-diff-stationery-start-finish-regular-scale  $k_{stat,1}$ )
           (_second-diff-stationery-start-finish-regular-scale  $k_{stat,2}$ )
           (_diff-square-integration-regular-scale  $k_{sqr}$ )
           (_diff-mat buffer for  $\mathbf{D}^k$ )
           (_diff-mat-list buffer for  $\{\mathbf{D}^1, \mathbf{D}^2, \dots, \mathbf{D}^K\}$ )
           (_extended-diff-mat-list buffer for  $\{\hat{\mathbf{D}}_1, \hat{\mathbf{D}}_2, \dots, \hat{\mathbf{D}}_K\}$ )
           (_ineq-const-matrix buffer for  $\mathbf{C}_p$ )
           (_ineq-const-vector buffer for  $\mathbf{d}_p$ )

```

B スプラインを利用した軌道のクラス .

B スプラインベクトル・行列, 制御点ベクトル・ベクトル, 微分行列, 瞬時コンフィギュレーションの取得や制御点ベクトルの更新のためのメソッドが定義されている .

B スプライン軌道を定めるために, 初期化時に以下を与える

start-time t_s 初期時刻

finish-time t_f 終端時刻

num-control-point N_{ctrl} 制御点の個数

bspline-order n B スプラインのオーダー

dim-instant-config $N_{\bar{q}}$ 瞬時コンフィギュレーションの次元

ある時刻の瞬時コンフィギュレーション $\bar{\mathbf{q}}(t) \in \mathbb{R}^{N_{\bar{q}}}$ の j 番目の要素 $\bar{q}_j(t) \in \mathbb{R}$ を次式で表す .

$$\bar{q}_j(t) = \sum_{i=0}^{N_{ctrl}-1} p_{j,i} b_{i,n}(t) = \mathbf{p}_j^T \mathbf{b}_n(t) \quad (j = 1, 2, \dots, N_{\bar{q}}) \quad (4.253)$$

ただし ,

$$\mathbf{p}_j = \begin{pmatrix} p_{j,0} \\ p_{j,1} \\ \vdots \\ p_{j,N_{ctrl}-1} \end{pmatrix} \in \mathbb{R}^{N_{ctrl}} \quad (j = 1, 2, \dots, N_{\bar{q}}) \quad (4.254)$$

$$\mathbf{b}_n(t) = \begin{pmatrix} b_{0,n}(t) \\ b_{1,n}(t) \\ \vdots \\ b_{N_{ctrl}-1,n}(t) \end{pmatrix} \in \mathbb{R}^{N_{ctrl}} \quad (4.255)$$

$b_{i,n}(t)$ は B スプライン基底関数である . また , $p_{j,i}$ をそれぞれ制御点と呼ぶ .

したがって, $\bar{q}(t)$ は次式で表される .

$$\bar{q}(t) = \begin{pmatrix} \bar{q}_1(t) \\ \vdots \\ \bar{q}_{N_{\bar{q}}}(t) \end{pmatrix} = \begin{pmatrix} \mathbf{p}_1^T \mathbf{b}_n(t) \\ \mathbf{p}_2^T \mathbf{b}_n(t) \\ \vdots \\ \mathbf{p}_{N_{\bar{q}}}^T \mathbf{b}_n(t) \end{pmatrix} = \mathbf{P} \mathbf{b}_n(t) \quad (4.256)$$

ただし ,

$$\mathbf{P} = \begin{pmatrix} \mathbf{p}_1^T \\ \mathbf{p}_2^T \\ \vdots \\ \mathbf{p}_{N_{\bar{q}}}^T \end{pmatrix} \in \mathbb{R}^{N_{\bar{q}} \times N_{ctrl}} \quad (4.257)$$

また, $\bar{q}(t)$ は, 制御点を縦に並べたベクトルを分離して次式のようにも表される .

$$\bar{q}(t) = \begin{pmatrix} \mathbf{b}_n^T(t) \mathbf{p}_1 \\ \mathbf{b}_n^T(t) \mathbf{p}_2 \\ \vdots \\ \mathbf{b}_n^T(t) \mathbf{p}_{N_{\bar{q}}} \end{pmatrix} = \begin{pmatrix} \mathbf{b}_n^T(t) & & \mathbf{O} \\ & \mathbf{b}_n^T(t) & \\ & & \ddots \\ \mathbf{O} & & \mathbf{b}_n^T(t) \end{pmatrix} \begin{pmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \\ \vdots \\ \mathbf{p}_{N_{\bar{q}}} \end{pmatrix} = \mathbf{B}_n(t) \mathbf{p} \quad (4.258)$$

ただし ,

$$\mathbf{B}_n(t) = \begin{pmatrix} \mathbf{b}_n^T(t) & & \mathbf{O} \\ & \mathbf{b}_n^T(t) & \\ & & \ddots \\ \mathbf{O} & & \mathbf{b}_n^T(t) \end{pmatrix} \in \mathbb{R}^{N_{\bar{q}} \times N_{ctrl} N_{\bar{q}}}, \quad \mathbf{p} = \begin{pmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \\ \vdots \\ \mathbf{p}_{N_{\bar{q}}} \end{pmatrix} \in \mathbb{R}^{N_{ctrl} N_{\bar{q}}} \quad (4.259)$$

B スプラインによる軌道表現の詳細については第??節参照 .

```

:init key (name) [method]
    (start-time 0.0)
    (finish-time 10.0)
    (num-control-point 10)
    (bspline-order 3)
    (dim-instant-config 1)
    (stationery-start-finish-regular-scale 1.0)
    (zero-diff-stationery-start-finish-regular-scale 0.0)
    (first-diff-stationery-start-finish-regular-scale stationery-start-finish-regular-scale)
    (second-diff-stationery-start-finish-regular-scale stationery-start-finish-regular-scale)
    (diff-square-integration-regular-scale 1.0)

Initialize instance

:start-time [method]
    return  $t_s$ 

:finish-time [method]
    return  $t_s$ 

:num-control-point [method]
    return  $N_{ctrl}$ 

```

:dim-instant-confing

[method]

return $N_{\bar{q}}$

:dim-control-vector

[method]

return $\dim(\mathbf{p}) := N_{ctrl}N_{\bar{q}}$

:bspline-vector *tm* *ℰkey* (order-offset 0)

[method]

$$\mathbf{b}_n(t) := \begin{pmatrix} b_{0,n}(t) \\ b_{1,n}(t) \\ \vdots \\ b_{N_{ctrl}-1,n}(t) \end{pmatrix} \in \mathbb{R}^{N_{ctrl}} \quad (4.260)$$

return $\mathbf{b}_n(t)$

:bspline-matrix *tm* *ℰkey* (order-offset 0)

[method]

$$\mathbf{B}_n(t) := \begin{pmatrix} \mathbf{b}_n^T(t) & & & \mathbf{O} \\ & \mathbf{b}_n^T(t) & & \\ & & \ddots & \\ \mathbf{O} & & & \mathbf{b}_n^T(t) \end{pmatrix} \in \mathbb{R}^{N_{\bar{q}} \times N_{ctrl}N_{\bar{q}}} \quad (4.261)$$

return $\mathbf{B}_n(t)$

:control-vector

[method]

$$\mathbf{p} := \begin{pmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_{N_{\bar{q}}} \end{pmatrix} \in \mathbb{R}^{N_{ctrl}N_{\bar{q}}} \quad (4.262)$$

return \mathbf{p}

:control-matrix

[method]

$$\mathbf{P} := \begin{pmatrix} \mathbf{p}_1^T \\ \vdots \\ \mathbf{p}_{N_{\bar{q}}}^T \end{pmatrix} \in \mathbb{R}^{N_{\bar{q}} \times N_{ctrl}} \quad (4.263)$$

return \mathbf{P}

:differential-matrix *ℰkey* (diff-order 1)

[method]

$$\mathbf{D} := \frac{1}{h} \begin{pmatrix} 1 & -1 & & & \mathbf{O} \\ & 1 & -1 & & \\ & & \ddots & \ddots & \\ & & & \ddots & -1 \\ \mathbf{O} & & & & 1 \end{pmatrix} \in \mathbb{R}^{N_{ctrl} \times N_{ctrl}} \quad (4.264)$$

return \mathbf{D}^k

:extended-differential-matrix *ℰkey (diff-order 1)*

[method]

$$\hat{\mathbf{D}}_k := \begin{pmatrix} (\mathbf{D}^k)^T & & \mathbf{O} \\ & \ddots & \\ \mathbf{O} & & (\mathbf{D}^k)^T \end{pmatrix} \in \mathbb{R}^{N_{ctrl}N_{\bar{q}} \times N_{ctrl}N_{\bar{q}}} \quad (4.265)$$

return $\hat{\mathbf{D}}_k$

:instant-config *tm*

[method]

$$\text{return } \bar{\mathbf{q}}(t) = \begin{pmatrix} \mathbf{p}_1^T \mathbf{b}_n(t) \\ \vdots \\ \mathbf{p}_{N_{\bar{q}}}^T \mathbf{b}_n(t) \end{pmatrix} = \mathbf{P} \mathbf{b}_n(t) = \mathbf{B}_n(t) \mathbf{p} \in \mathbb{R}^{N_{\bar{q}}}$$

:instant-config-dot *tm ℰkey (diff-order 1)*

[method]

$$\text{return } \bar{\mathbf{q}}^{(k)}(t) = \frac{d^{(k)} \bar{\mathbf{q}}(t)}{dt^{(k)}} = \mathbf{P} \mathbf{D}^k \mathbf{b}_{n-k}(t)$$

:set-control-vector *control-vector-new ℰkey (relative? nil)*

[method]

Set $\mathbf{p} \in \mathbb{R}^{N_{ctrl}N_{\bar{q}}}$.

:set-control-vector-from-instant-config *instant-config*

[method]

Set $\mathbf{p} \in \mathbb{R}^{N_{ctrl}N_{\bar{q}}}$ from $\bar{\mathbf{q}} \in \mathbb{R}^{N_{\bar{q}}}$.

:convert-instant-inequality-constraint-matrix-for-control-vector *ℰkey (instant-ineq-matrix) (update? nil)* [method]

$$\bar{\mathbf{q}}(t) = \begin{pmatrix} \bar{q}_1(t) \\ \vdots \\ \bar{q}_{N_{\bar{q}}}(t) \end{pmatrix} = \begin{pmatrix} \sum_{i=0}^{N_{ctrl}-1} p_{1,i} b_{i,n}(t) \\ \sum_{i=0}^{N_{ctrl}-1} p_{2,i} b_{i,n}(t) \\ \vdots \\ \sum_{i=0}^{N_{ctrl}-1} p_{N_{\bar{q}},i} b_{i,n}(t) \end{pmatrix} = \begin{pmatrix} \mathbf{p}_1^T \mathbf{b}_n(t) \\ \mathbf{p}_2^T \mathbf{b}_n(t) \\ \vdots \\ \mathbf{p}_{N_{\bar{q}}}^T \mathbf{b}_n(t) \end{pmatrix} = \mathbf{P} \mathbf{b}_n(t) \quad (4.266)$$

ただし,

$$\mathbf{P} = \begin{pmatrix} \mathbf{p}_1^T \\ \mathbf{p}_2^T \\ \vdots \\ \mathbf{p}_{N_{\bar{q}}}^T \end{pmatrix} = (\tilde{\mathbf{p}}_0 \quad \tilde{\mathbf{p}}_1 \quad \cdots \quad \tilde{\mathbf{p}}_{N_{ctrl}-1}) \quad (4.267)$$

$$\tilde{\mathbf{p}}_i = \begin{pmatrix} p_{1,i} \\ p_{2,i} \\ \vdots \\ p_{N_{\bar{q}},i} \end{pmatrix} \quad (i = 0, 1, \dots, N_{ctrl} - 1) \quad (4.268)$$

ここで制御点 \mathbf{p} が次式を満たすとする.

$$\mathbf{c}^T \tilde{\mathbf{p}}_i \geq d \quad (i = 0, 1, \dots, N_{ctrl} - 1) \quad (4.269)$$

つまり,

$$\begin{pmatrix} c_1 & c_2 & \cdots & c_{N_{\bar{q}}} \end{pmatrix} \begin{pmatrix} p_{1,i} \\ p_{2,i} \\ \vdots \\ p_{N_{\bar{q}},i} \end{pmatrix} = \sum_{j=1}^{N_{\bar{q}}} c_j p_{j,i} \geq d \quad (i = 0, 1, \dots, N_{ctrl} - 1) \quad (4.270)$$

このとき ,

$$\mathbf{c}^T \bar{\mathbf{q}}(t) = \begin{pmatrix} c_1 & c_2 & \cdots & c_{N_{\bar{q}}} \end{pmatrix} \begin{pmatrix} \sum_{i=0}^{N_{ctrl}-1} p_{1,i} b_{i,n}(t) \\ \sum_{i=0}^{N_{ctrl}-1} p_{2,i} b_{i,n}(t) \\ \vdots \\ \sum_{i=0}^{N_{ctrl}-1} p_{N_{\bar{q}},i} b_{i,n}(t) \end{pmatrix} \quad (4.271)$$

$$= \sum_{j=1}^{N_{\bar{q}}} c_j \sum_{i=0}^{N_{ctrl}-1} p_{j,i} b_{i,n}(t) \quad (4.272)$$

$$= \sum_{i=0}^{N_{ctrl}-1} \left(\sum_{j=1}^{N_{\bar{q}}} c_j p_{j,i} \right) b_{i,n}(t) \quad (4.273)$$

$$\geq d \sum_{i=0}^{N_{ctrl}-1} b_{i,n}(t) \quad (4.274)$$

$$= d \quad (4.275)$$

したがって ,

$$\mathbf{C}_{\bar{q}} \bar{\mathbf{q}}(t) \geq \mathbf{d}_{\bar{q}} \quad (4.276)$$

$$\Leftrightarrow \mathbf{C}_{\bar{q}} \bar{\mathbf{p}}_i \geq \mathbf{d}_{\bar{q}} \quad (i = 0, 1, \dots, N_{ctrl} - 1) \quad (4.277)$$

$$\Leftrightarrow \begin{matrix} & N_{ctrl} & N_{ctrl} & & N_{ctrl} \\ N_{ineq} & \begin{pmatrix} \mathbf{C}_{p,0,1} & \mathbf{C}_{p,0,2} & \cdots & \mathbf{C}_{p,0,N_{\bar{q}}} \\ \mathbf{C}_{p,1,1} & \mathbf{C}_{p,1,2} & \cdots & \mathbf{C}_{p,1,N_{\bar{q}}} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{C}_{p,N_{ctrl}-1,1} & \mathbf{C}_{p,N_{ctrl}-1,2} & \cdots & \mathbf{C}_{p,N_{ctrl}-1,N_{\bar{q}}} \end{pmatrix} & \begin{pmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \\ \vdots \\ \mathbf{p}_{N_{\bar{q}}} \end{pmatrix} & \geq & \begin{pmatrix} \mathbf{d}_{\bar{q}} \\ \mathbf{d}_{\bar{q}} \\ \vdots \\ \mathbf{d}_{\bar{q}} \end{pmatrix} \end{matrix} \quad (4.278)$$

$$\Leftrightarrow \mathbf{C}_p \mathbf{p} \geq \mathbf{d}_p \quad (4.279)$$

ただし ,

$$\mathbf{C}_{\bar{q}} = \begin{pmatrix} c_1 & c_2 & \cdots & c_{N_{\bar{q}}} \end{pmatrix} \in \mathbb{R}^{N_{ineq} \times N_{\bar{q}}} \quad (4.280)$$

i 番目

$$\mathbf{C}_{p,i,j} = \begin{pmatrix} 0 & \cdots & 0 & c_j & 0 & \cdots & 0 \end{pmatrix} \in \mathbb{R}^{N_{ineq} \times N_{ctrl}} \quad (4.281)$$

$$(i = 0, 1, \dots, N_{ctrl} - 1, j = 1, 2, \dots, N_{\bar{q}}) \quad (4.282)$$

このメソッドは $\mathbf{C}_{\bar{q}} \in \mathbb{R}^{N_{ineq} \times N_{\bar{q}}}$ を受け取り , $\mathbf{C}_p \in \mathbb{R}^{N_{ctrl} N_{ineq} \times N_{ctrl} N_{\bar{q}}}$ を返す .

:convert-instant-inequality-constraint-vector-for-control-vector *ℰkey* (*instant-ineq-vector*) [method]
(*update?* *nil*)

このメソッドは $\mathbf{d}_{\bar{q}} \in \mathbb{R}^{N_{ineq}}$ を受け取り , $\mathbf{d}_p \in \mathbb{R}^{N_{ctrl} N_{ineq}}$ を返す .

:stationery-start-finish-regular-matrix *ℰkey* (*start-time* *start-time*) [method]
(*finish-time* *finish-time*)
(*update?* *nil*)

$$\mathbf{W}_{stat} = k_{stat,0} \mathbf{B}_n^T(t_s) \mathbf{B}_n(t_s) + k_{stat,0} \mathbf{B}_n^T(t_f) \mathbf{B}_n(t_f) \quad (4.283)$$

$$+ k_{stat,1} (\mathbf{B}_{n-1}(t_s) \hat{\mathbf{D}}_1)^T (\mathbf{B}_{n-1}(t_s) \hat{\mathbf{D}}_1) + k_{stat,1} (\mathbf{B}_{n-1}(t_f) \hat{\mathbf{D}}_1)^T (\mathbf{B}_{n-1}(t_f) \hat{\mathbf{D}}_1) \quad (4.284)$$

$$+ k_{stat,2} (\mathbf{B}_{n-2}(t_s) \hat{\mathbf{D}}_2)^T (\mathbf{B}_{n-2}(t_s) \hat{\mathbf{D}}_2) + k_{stat,2} (\mathbf{B}_{n-2}(t_f) \hat{\mathbf{D}}_2)^T (\mathbf{B}_{n-2}(t_f) \hat{\mathbf{D}}_2) \quad (4.285)$$

return $\mathbf{W}_{stat} \in \mathbb{R}^{N_{ctrl} N_{\bar{q}} \times N_{ctrl} N_{\bar{q}}}$


```

(dim-eom-rot-task  $\dim(\mathbf{e}^{eom-rot})$ )
(dim-cog-task  $\dim(\mathbf{e}^{cog})$ )
(dim-ang-moment-task  $\dim(\mathbf{e}^{ang-moment})$ )
(dim-torque-task  $\dim(\mathbf{e}^{trq})$ )
(dim-posture-task  $\dim(\mathbf{e}^{posture})$ )
(dim-task  $\dim(\mathbf{e})$ )
(kin-task-scale  $k_{kin}$ )
(kin-task-scale-mat-list-func function returning list of  $K_{kin}$ )
(eom-trans-task-scale  $k_{eom-trans}$ )
(eom-rot-task-scale  $k_{eom-rot}$ )
(cog-task-scale  $k_{cog}$ )
(ang-moment-task-scale  $k_{ang-moment}$ )
(torque-task-scale  $k_{trq}$ )
(posture-task-scale  $k_{posture}$ )
(torque-regular-scale  $k_{trq}$ )
(stationery-start-finish-regular-scale  $k_{stat}$ )
(first-diff-square-integration-regular-scale  $k_{sqr,1}$ )
(second-diff-square-integration-regular-scale  $k_{sqr,2}$ )
(third-diff-square-integration-regular-scale  $k_{sqr,3}$ )
(norm-regular-scale-max  $k_{max}$ )
(norm-regular-scale-offset  $k_{off}$ )
(variant-joint-list  $\mathcal{J}_{var}$ )
(invariant-joint-list  $\mathcal{J}_{invar}$ )
(drive-joint-list  $\mathcal{J}_{drive}$ )
(posture-joint-list  $\mathcal{J}_{posture}$ )
(kin-task-time-list time list for kinematics task)
(eom-task-time-list time list for eom task)
(centroid-task-time-list time list for centroid task)
(posture-task-time-list time list for posture task)
(kin-target-coords-list-func function returning  $\mathcal{T}^{kin-trg}$ )
(kin-attention-coords-list-func function returning  $\mathcal{T}^{kin-att}$ )
(contact-target-coords-list-func function returning  $\mathcal{T}^{cnt-trg}$ )
(contact-attention-coords-list-func function returning  $\mathcal{T}^{cnt-att}$ )
(contact-constraint-list-func function returning list of contact-constraint)
(posture-joint-angle-list  $\boldsymbol{\theta}^{trg}$ )
(variant-joint-angle-margin margin of  $\boldsymbol{\theta}$  [deg] [mm])
(invariant-joint-angle-margin margin of  $\boldsymbol{\phi}$  [deg] [mm])
(collision-pair-list list of bodyset-link or body pair)
(collision-distance-margin-list list of collision distance margin)
(task-jacobi buffer for  $\frac{\partial \mathbf{e}}{\partial \mathbf{q}}$ )
(collision-theta-inequality-constraint-matrix buffer for  $\mathbf{C}_{col,\theta}$ )
(collision-phi-inequality-constraint-matrix buffer for  $\mathbf{C}_{col,\phi}$ )
(collision-inequality-constraint-vector buffer for  $\mathbf{C}_{col}$ )

```

B スブラインを利用した動的動作生成のためのコンフィギュレーション \mathbf{q} とタスク関数 $\mathbf{e}(\mathbf{q})$ のクラス .

コンフィギュレーション q の取得・更新, タスク関数 $e(q)$ の取得, タスク関数のヤコビ行列 $\frac{\partial e(q)}{\partial q}$ の取得, コンフィギュレーションの等式・不等式制約 A, b, C, d の取得のためのメソッドが定義されている。

初期化

コンフィギュレーション・タスク関数を定めるために, 初期化時に以下を与える

- ロボット・環境
 - robot-environment ロボット・環境を表す robot-environment クラスのインスタンス
 - variant-joint-list \mathcal{J}_{var} 時変関節
 - invariant-joint-list \mathcal{J}_{invar} 時不変関節 (与えなければ時不変関節は考慮されない)
 - drive-joint-list \mathcal{J}_{drive} 駆動関節 (与えなければ関節駆動トルクは考慮されない)
- B スプライン軌道
 - theta-bst 時変関節位置 θ の B スプライン軌道のインスタンス
 - cog-bst 重心位置 c の B スプライン軌道のインスタンス
 - ang-moment-bst 角運動量 L の B スプライン軌道のインスタンス
 - wrench-bst 接触レンチ \hat{w} の B スプライン軌道のインスタンス
 - torque-bst 関節トルク τ の B スプライン軌道のインスタンス
- タスク関数のサンプリング時刻
 - kin-task-time-list 幾何到達拘束 e^{kin} の時刻のリスト
 - eom-task-time-list 並進運動方程式 $e^{eom-trans}$, 回転運動方程式 $e^{eom-rot}$ の時刻リスト
 - centroid-task-time-list 重心位置 e^{cog} , 角運動量 $e^{ang-moment}$ の時刻リスト
 - posture-task-time-list 関節角目標 $e^{posture}$ の時刻リスト
- 幾何拘束
 - kin-target-coords-list-func 幾何到達目標位置姿勢リスト $\mathcal{T}^{kin-trg}$ を返す関数
 - kin-attention-coords-list-func 幾何到達着目位置姿勢リスト $\mathcal{T}^{kin-att}$ を返す関数
- 接触拘束
 - contact-target-coords-list-func 接触目標位置姿勢リスト $\mathcal{T}^{cnt-trg}$ を返す関数
 - contact-attention-coords-list-func 接触着目位置姿勢リスト $\mathcal{T}^{cnt-att}$ を返す関数
 - contact-constraint-list-func 接触レンチ制約リストを返す関数
- コンフィギュレーション拘束 (必要な場合のみ)
 - posture-joint-list $\mathcal{J}_{posture}$ 着目関節リスト
 - posture-joint-angle-list $\bar{\theta}^{trg}$ 着目関節の目標関節角
- 干渉回避拘束 (必要な場合のみ)
 - collision-pair-list 干渉回避する bodyset-link もしくは body のペアのリスト
 - collision-distance-margin 干渉回避の距離マージン (全てのペアで同じ値の場合)
 - collision-distance-margin-list 干渉回避の距離マージンのリスト (ペアごとに異なる値の場合)
- 目的関数の重み
 - kin-task-scale k_{kin} 幾何到達拘束タスクの重み
 - kin-task-scale-mat-list-func 幾何到達拘束タスクの重み行列 K_{kin} を返す関数
 - eom-trans-task-scale $k_{eom-trans}$ 並進運動方程式タスクの重み

eom-rot-task-scale $k_{eom-rot}$ 回転運動方程式タスクの重み
 cog-task-scale k_{cog} 重心位置タスクの重み
 ang-moment-task-scale $k_{ang-moment}$ 角運動量タスクの重み
 torque-task-scale k_{trq} 関節トルクの釣り合いタスクの重み
 posture-task-scale $k_{posture}$ 目標関節角タスクの重み
 torque-regular-scale k_{trq} トルク正則化の重み
 stationery-start-finish-regular-scale k_{stat} 初期・終端静止正則化の重み
 first-diff-square-integration-regular-scale $k_{sqr,1}$ 速度正則化の重み
 second-diff-square-integration-regular-scale $k_{sqr,2}$ 加速度正則化の重み
 third-diff-square-integration-regular-scale $k_{sqr,3}$ 躍度正則化の重み
 norm-regular-scale-max k_{max} コンフィギュレーション更新量正則化の重み最大値
 norm-regular-scale-offset k_{off} コンフィギュレーション更新量正則化の重みオフセット

コンフィギュレーション

動的動作は各瞬間において以下の瞬時状態 $\bar{q}(t)$ を定めることで表現される．

$$\bar{q}(t) := \begin{pmatrix} \theta(t) \\ c(t) \\ L(t) \\ \hat{w}(t) \\ \tau(t) \\ \phi \end{pmatrix} \quad (4.290)$$

$\theta \in \mathbb{R}^{N_{var-joint}}$ 時変関節位置 [rad] [m]

$c \in \mathbb{R}^3$ 重心位置 [m]

$L \in \mathbb{R}^3$ 角運動量 [kgm²/s]

$\hat{w} \in \mathbb{R}^{6N_{cnt}}$ 接触レンチ [N] [Nm]

$\tau \in \mathbb{R}^{N_{drive-joint}}$ 関節トルク [Nm] [N]

$\phi \in \mathbb{R}^{N_{invar-joint}}$ 時不変関節位置 [rad] [m]

\hat{w} は次式のように，全接触部位でのワールド座標系での力・モーメントを並べたベクトルである．

$$\hat{w} = \begin{pmatrix} w_1^T & w_2^T & \cdots & w_{N_{cnt}}^T \end{pmatrix}^T \quad (4.291)$$

$$= \begin{pmatrix} f_1^T & n_1^T & f_2^T & n_2^T & \cdots & f_{N_{cnt}}^T & n_{N_{cnt}}^T \end{pmatrix}^T \quad (4.292)$$

本クラスでは，瞬時状態 $\bar{q}(t)$ の軌道を B スプラインで表現する．設計対称のコンフィギュレーション q は以下から構成される．

$$q := \begin{pmatrix} p_\theta \\ p_c \\ p_L \\ p_{\hat{w}} \\ p_\tau \\ \phi \end{pmatrix} \quad (4.293)$$

$\mathbf{p}_\theta \in \mathbb{R}^{N_{var-joint} N_{\theta-ctrl}}$ 時変関節位置の制御点 [rad] [m]

$\mathbf{p}_c \in \mathbb{R}^{3N_{c-ctrl}}$ 重心位置の制御点 [m]

$\mathbf{p}_L \in \mathbb{R}^{3N_{L-ctrl}}$ 角運動量の制御点 [kgm²/s]

$\mathbf{p}_{\hat{w}} \in \mathbb{R}^{6N_{cnt} N_{\hat{w}-ctrl}}$ 接触レンチの制御点 [N] [Nm]

$\mathbf{p}_\tau \in \mathbb{R}^{N_{drive-joint} N_{\tau-ctrl}}$ 関節トルクの制御点 [Nm] [N]

$\phi \in \mathbb{R}^{N_{invar-joint}}$ 時不変関節位置 [rad] [m]

制御点とは，B スプライン基底関数の重み係数を意味する．

タスク関数

瞬時状態 $\bar{\mathbf{q}}(t)$ に関するタスク関数 $\bar{\mathbf{e}}(\bar{\mathbf{q}}(t))$ は以下から構成される．

$$\bar{\mathbf{e}}(\bar{\mathbf{q}}) = \begin{pmatrix} \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}, \phi) \\ \bar{\mathbf{e}}^{eom-trans}(\mathbf{c}, \hat{\mathbf{w}}) \\ \bar{\mathbf{e}}^{eom-rot}(\boldsymbol{\theta}, \mathbf{c}, \mathbf{L}, \hat{\mathbf{w}}, \phi) \\ \bar{\mathbf{e}}^{cog}(\boldsymbol{\theta}, \mathbf{c}, \phi) \\ \bar{\mathbf{e}}^{ang-moment}(\boldsymbol{\theta}, \mathbf{L}, \phi) \\ \bar{\mathbf{e}}^{trq}(\boldsymbol{\theta}, \hat{\mathbf{w}}, \boldsymbol{\tau}, \phi) \\ \bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}) \end{pmatrix} \quad (4.294)$$

$\bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}, \phi) \in \mathbb{R}^{6\bar{N}_{kin}(t)}$ 幾何到達拘束 [rad] [m]

$$\bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}, \phi) = \begin{pmatrix} \bar{\mathbf{e}}_1^{kin}(\boldsymbol{\theta}, \phi) \\ \bar{\mathbf{e}}_2^{kin}(\boldsymbol{\theta}, \phi) \\ \vdots \\ \bar{\mathbf{e}}_{\bar{N}_{kin}(t)}^{kin}(\boldsymbol{\theta}, \phi) \end{pmatrix} \quad (4.295)$$

$$\bar{\mathbf{e}}_m^{kin}(\boldsymbol{\theta}, \phi) = \begin{pmatrix} \mathbf{p}_m^{kin-trg}(\boldsymbol{\theta}, \phi) - \mathbf{p}_m^{kin-att}(\boldsymbol{\theta}, \phi) \\ \mathbf{a} \left(\mathbf{R}_m^{kin-trg}(\boldsymbol{\theta}, \phi) \mathbf{R}_m^{kin-att}(\boldsymbol{\theta}, \phi)^T \right) \end{pmatrix} \in \mathbb{R}^6 \quad (m = 1, 2, \dots, \bar{N}_{kin}(t)) \quad (4.296)$$

$\mathbf{a}(\mathbf{R})$ は姿勢行列 \mathbf{R} の等価角軸ベクトルを表す．

$\bar{\mathbf{e}}^{eom-trans}(\mathbf{c}, \hat{\mathbf{w}}) \in \mathbb{R}^3$ 並進運動方程式 [kg m/s²]

$$\bar{\mathbf{e}}^{eom-trans}(\mathbf{c}, \hat{\mathbf{w}}) = m\ddot{\mathbf{c}} - \left\{ \sum_{m=1}^{N_{cnt}} \mathbf{f}_m - m\mathbf{g} + \sum_{m=1}^{N_{ex}} \mathbf{f}_m^{ex} \right\} \quad (4.297)$$

$\bar{\mathbf{e}}^{eom-rot}(\boldsymbol{\theta}, \mathbf{c}, \mathbf{L}, \hat{\mathbf{w}}, \phi) \in \mathbb{R}^3$ 回転運動方程式 [kg m²/s²]

$$\begin{aligned} \bar{\mathbf{e}}^{eom-rot}(\boldsymbol{\theta}, \mathbf{c}, \mathbf{L}, \hat{\mathbf{w}}, \phi) &= \dot{\mathbf{L}} - \left(\sum_{m=1}^{N_{cnt}} \{ (\mathbf{p}_m^{cnt-trg}(\boldsymbol{\theta}, \phi) - \mathbf{c}) \times \mathbf{f}_m + \mathbf{n}_m \} \right. \\ &\quad \left. + \sum_{m=1}^{N_{ex}} \{ (\mathbf{p}_m^{ex}(\boldsymbol{\theta}, \phi) - \mathbf{c}) \times \mathbf{f}_m^{ex} + \mathbf{n}_m^{ex} \} \right) \end{aligned} \quad (4.298)$$

$\bar{\mathbf{e}}^{cog}(\boldsymbol{\theta}, \mathbf{c}, \phi) \in \mathbb{R}^3$ 重心位置 [m]

$$\bar{\mathbf{e}}^{cog}(\boldsymbol{\theta}, \mathbf{c}, \phi) = \mathbf{p}_G(\boldsymbol{\theta}, \phi) - \mathbf{c} \quad (4.299)$$

$\bar{e}^{ang-moment}(\boldsymbol{\theta}, \mathbf{L}, \phi) \in \mathbb{R}^3$ 角運動量 [kg m²/s]

$$\bar{e}^{ang-moment}(\boldsymbol{\theta}, \mathbf{L}, \phi) = \mathbf{L} - \left\{ \mathbf{A}_\theta(\boldsymbol{\theta}, \phi) \dot{\boldsymbol{\theta}} + \mathbf{A}_\phi(\boldsymbol{\theta}, \phi) \dot{\phi} \right\} \quad (4.300)$$

$\bar{e}^{trq}(\boldsymbol{\theta}, \hat{\mathbf{w}}, \boldsymbol{\tau}, \phi) \in \mathbb{R}^{N_{drive-joint}}$ 関節トルクの釣り合い [rad] [m]

$$\begin{aligned} \bar{e}^{trq}(\boldsymbol{\theta}, \hat{\mathbf{w}}, \boldsymbol{\tau}, \phi) &= \sum_{m=1}^{N_{cnt}} \{ (\mathbf{p}_m^{cnt-trg}(\boldsymbol{\theta}, \phi) - \mathbf{c}) \times \mathbf{f}_m + \mathbf{n}_m \} \\ &\quad + \sum_{m=1}^{N_{ex}} \{ (\mathbf{p}_m^{ex}(\boldsymbol{\theta}, \phi) - \mathbf{c}) \times \mathbf{f}_m^{ex} + \mathbf{n}_m^{ex} \} \end{aligned} \quad (4.301)$$

$\bar{e}^{posture}(\boldsymbol{\theta}) \in \mathbb{R}^{N_{posture-joint}}$ 関節角目標 [rad] [m]

$$\bar{e}^{posture}(\boldsymbol{\theta}) = (\bar{\boldsymbol{\theta}}^{trg} - \bar{\boldsymbol{\theta}}) \quad (4.302)$$

瞬時状態 $\bar{\mathbf{q}}(t)$ の軌道を B スプラインで表現することで, 設計対称のコンフィギュレーション \mathbf{q} に関するタスク関数 $\mathbf{e}(\mathbf{q})$ は以下から構成される.

$$\mathbf{e}(\mathbf{q}) = \begin{pmatrix} e^{kin}(\mathbf{p}_\theta, \phi) \\ e^{eom-trans}(\mathbf{p}_c, \mathbf{p}_{\hat{\mathbf{w}}}) \\ e^{eom-rot}(\mathbf{p}_\theta, \mathbf{p}_c, \mathbf{p}_L, \mathbf{p}_{\hat{\mathbf{w}}}, \phi) \\ e^{cog}(\mathbf{p}_\theta, \mathbf{p}_c, \phi) \\ e^{ang-moment}(\mathbf{p}_\theta, \mathbf{p}_L, \phi) \\ e^{trq}(\mathbf{p}_\theta, \mathbf{p}_{\hat{\mathbf{w}}}, \mathbf{p}_\tau, \phi) \\ e^{posture}(\mathbf{p}_\theta) \end{pmatrix} \quad (4.303)$$

ただし,

$$\mathbf{e}^*(\mathbf{q}) = \begin{pmatrix} \bar{\mathbf{e}}^*(\bar{\mathbf{q}}(t_1)) \\ \vdots \\ \bar{\mathbf{e}}^*(\bar{\mathbf{q}}(t_{N_{tm}})) \end{pmatrix} \in \mathbb{R}^{N_{tm} \dim(\bar{\mathbf{e}}^*(\bar{\mathbf{q}})(t))} \quad (4.304)$$

:init *key* (*name*) [method]

(*robot-env*)

(*variant-joint-list* (*send robot-env :variant-joint-list*))

(*invariant-joint-list* (*send robot-env :invariant-joint-list*))

(*drive-joint-list* (*send robot-env :drive-joint-list*))

(*posture-joint-list*)

(*kin-task-time-list*)

(*eom-task-time-list*)

(*centroid-task-time-list*)

(*posture-task-time-list*)

(*theta-bst*)

(*cog-bst*)

(*ang-moment-bst*)

(*wrench-bst*)

(*torque-bst*)

(*kin-target-coords-list-func*)

(*kin-attention-coords-list-func*)

(contact-target-coords-list-func)
(contact-attention-coords-list-func)
(contact-constraint-list-func)
(posture-joint-angle-list)
(variant-joint-angle-margin 3.0)
(invariant-joint-angle-margin 3.0)
(collision-pair-list)
(collision-distance-margin 0.01)
(collision-distance-margin-list)
(kin-task-scale 1.0)
(kin-task-scale-mat-list-func)
(eom-trans-task-scale 1.0)
(eom-rot-task-scale 1.0)
(cog-task-scale 1.0)
(ang-moment-task-scale 1.0)
(torque-task-scale 1.0)
(posture-task-scale 0.001)
(torque-regular-scale 1.000000e-04)
(stationery-start-finish-regular-scale 1.000000e-04)
(first-diff-square-integration-regular-scale 1.000000e-07)
(second-diff-square-integration-regular-scale 1.000000e-07)
(third-diff-square-integration-regular-scale 1.000000e-07)
(norm-regular-scale-max 1.000000e-05)
(norm-regular-scale-offset 1.000000e-07)

Initialize instance

:robot-env	[method]
return robot-environment instance	
:variant-joint-list	[method]
return \mathcal{J}_{var}	
:invariant-joint-list	[method]
return \mathcal{J}_{invar}	
:drive-joint-list	[method]
return \mathcal{J}_{drive}	
:num-kin	[method]
return $N_{kin} := \mathcal{T}^{kin-trg} = \mathcal{T}^{kin-att} $	
:num-contact	[method]
return $N_{cnt} := \mathcal{T}^{cnt-trg} = \mathcal{T}^{cnt-att} $	
:num-variant-joint	[method]
return $N_{var-joint} := \mathcal{J}_{var} $	
:num-invariant-joint	[method]
return $N_{invar-joint} := \mathcal{J}_{invar} $	

:num-drive-joint	[method]
return $N_{drive-joint} := \mathcal{J}_{drive} $	
:num-posture-joint	[method]
return $N_{target-joint} := \mathcal{J}_{target} $	
:num-collision	[method]
return $N_{col} :=$ number of collision check pairs	
:dim-config	[method]
return $dim(\mathbf{q})$	
:dim-task	[method]
return $dim(\mathbf{e})$	
:theta-control-vector	[method]
return \mathbf{p}_θ	
:cog-control-vector	[method]
return \mathbf{p}_c	
:ang-moment-control-vector	[method]
return \mathbf{p}_L	
:wrench-control-vector	[method]
return $\mathbf{p}_{\hat{w}}$	
:torque-control-vector	[method]
return \mathbf{p}_τ	
:phi	[method]
return ϕ	
:config-vector	[method]
return \mathbf{q}	
:set-theta-control-vector <i>control-vector-new</i> <i>ℰkey</i> (<i>relative?</i> <i>nil</i>)	[method]
Set \mathbf{p}_θ .	
:set-cog-control-vector <i>control-vector-new</i> <i>ℰkey</i> (<i>relative?</i> <i>nil</i>)	[method]
Set \mathbf{p}_c .	
:set-ang-moment-control-vector <i>control-vector-new</i> <i>ℰkey</i> (<i>relative?</i> <i>nil</i>)	[method]
Set \mathbf{p}_L .	
:set-wrench-control-vector <i>control-vector-new</i> <i>ℰkey</i> (<i>relative?</i> <i>nil</i>)	[method]
Set $\mathbf{p}_{\hat{w}}$.	
:set-torque-control-vector <i>control-vector-new</i> <i>ℰkey</i> (<i>relative?</i> <i>nil</i>)	[method]
Set \mathbf{p}_τ .	
:set-phi <i>phi-new</i> <i>ℰkey</i> (<i>relative?</i> <i>nil</i>)	[method]
Set ϕ .	

:set-config <i>config-new</i> <i>ℰkey</i> (<i>relative?</i> <i>nil</i>)	[method]
Set \mathbf{q} .	
:theta <i>tm</i> <i>ℰkey</i> (<i>diff-order</i> 0)	[method]
return $\boldsymbol{\theta}(t)$ [rad] [m]	
:cog <i>tm</i> <i>ℰkey</i> (<i>diff-order</i> 0)	[method]
return $\mathbf{c}(t)$ [m]	
:ang-moment <i>tm</i> <i>ℰkey</i> (<i>diff-order</i> 0)	[method]
return $\mathbf{L}(t)$ [kgm ² /s]	
:wrench <i>tm</i> <i>ℰkey</i> (<i>diff-order</i> 0)	[method]
return $\hat{\mathbf{w}}(t)$ [N] [Nm]	
:torque <i>tm</i> <i>ℰkey</i> (<i>diff-order</i> 0)	[method]
return $\boldsymbol{\tau}(t)$ [Nm] [N]	
:apply-config-to-robot <i>tm</i>	[method]
apply $\mathbf{q}(t)$ to robot.	
:kin-target-coords-list <i>tm</i>	[method]

$$T_m^{kin-trg} = \{\mathbf{p}_m^{kin-trg}, \mathbf{R}_m^{kin-trg}\} \quad (m = 1, 2, \dots, N_{kin}) \quad (4.305)$$

$$\text{return } \mathcal{T}^{kin-trg} := \{T_1^{kin-trg}, T_2^{kin-trg}, \dots, T_{N_{kin}}^{kin-trg}\}$$

:kin-attention-coords-list <i>tm</i>	[method]
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$$T_m^{kin-att} = \{\mathbf{p}_m^{kin-att}, \mathbf{R}_m^{kin-att}\} \quad (m = 1, 2, \dots, N_{kin}) \quad (4.306)$$

$$\text{return } \mathcal{T}^{kin-att} := \{T_1^{kin-att}, T_2^{kin-att}, \dots, T_{N_{kin}}^{kin-att}\}$$

:kin-scale-mat-list <i>tm</i>	[method]
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return list of K_{kin}

:contact-target-coords-list <i>tm</i>	[method]
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$$T_m^{cnt-trg} = \{\mathbf{p}_m^{cnt-trg}, \mathbf{R}_m^{cnt-trg}\} \quad (m = 1, 2, \dots, N_{cnt}) \quad (4.307)$$

$$\text{return } \mathcal{T}^{cnt-trg} := \{T_1^{cnt-trg}, T_2^{cnt-trg}, \dots, T_{N_{cnt}}^{cnt-trg}\}$$

:contact-attention-coords-list <i>tm</i>	[method]
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$$T_m^{cnt-att} = \{\mathbf{p}_m^{cnt-att}, \mathbf{R}_m^{cnt-att}\} \quad (m = 1, 2, \dots, N_{cnt}) \quad (4.308)$$

$$\text{return } \mathcal{T}^{cnt-att} := \{T_1^{cnt-att}, T_2^{cnt-att}, \dots, T_{N_{cnt}}^{cnt-att}\}$$

:contact-constraint-list <i>tm</i>	[method]
---	----------

return list of contact-constraint

:wrench-list tm [method]
 return $\{\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_{N_{cnt}}\}$

:force-list tm [method]
 return $\{\mathbf{f}_1, \mathbf{f}_2, \dots, \mathbf{f}_{N_{cnt}}\}$

:moment-list tm [method]
 return $\{\mathbf{n}_1, \mathbf{n}_2, \dots, \mathbf{n}_{N_{cnt}}\}$

:mass [method]
 return m [kg]

:mg-vec [method]
 return $m\mathbf{g}$ [kg m/s²]

:cog-from-model $\mathcal{E}key$ ($update?$ t) [method]
 return $\mathbf{p}_G(\mathbf{q})$ [m]

:kinematics-instant-task-value tm [method]

$$\bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t), \phi) = \begin{pmatrix} \bar{\mathbf{e}}_1^{kin}(\boldsymbol{\theta}(t), \phi) \\ \bar{\mathbf{e}}_2^{kin}(\boldsymbol{\theta}(t), \phi) \\ \vdots \\ \bar{\mathbf{e}}_{\bar{N}_{kin}(t)}^{kin}(\boldsymbol{\theta}(t), \phi) \end{pmatrix} \in \mathbb{R}^{6\bar{N}_{kin}(t)} \quad (4.309)$$

$$\bar{\mathbf{e}}_m^{kin}(\boldsymbol{\theta}, \phi) = \begin{pmatrix} \mathbf{p}_m^{kin-trg}(\boldsymbol{\theta}, \phi) - \mathbf{p}_m^{kin-att}(\boldsymbol{\theta}, \phi) \\ \mathbf{a} \left(\mathbf{R}_m^{kin-trg}(\boldsymbol{\theta}, \phi) \mathbf{R}_m^{kin-att}(\boldsymbol{\theta}, \phi)^T \right) \end{pmatrix} \in \mathbb{R}^6 \quad (m = 1, 2, \dots, \bar{N}_{kin}(t)) \quad (4.310)$$

$\mathbf{a}(\mathbf{R})$ は姿勢行列 \mathbf{R} の等価角軸ベクトルを表す .

return $\bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t), \phi) \in \mathbb{R}^{6\bar{N}_{kin}(t)}$

:kinematics-task-value $\mathcal{E}key$ ($update?$ t) [method]

$$\mathbf{e}^{kin}(\mathbf{p}_\theta, \phi) = \begin{pmatrix} \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t_1), \phi) \\ \vdots \\ \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t_{N_{tm-kin}}), \phi) \end{pmatrix} \in \mathbb{R}^{6N_{kin}} \quad \left(N_{kin} := \sum_{t=1}^{t_{N_{tm-kin}}} \bar{N}_{kin}(t) \right) \quad (4.311)$$

return $\mathbf{e}^{kin}(\mathbf{p}_\theta, \phi)$

:eom-trans-instant-task-value tm [method]

$$\bar{\mathbf{e}}^{eom-trans}(\mathbf{c}(t), \hat{\mathbf{w}}(t)) = m\ddot{\mathbf{c}} - \left\{ \sum_{\substack{m=1 \\ m \in contact}}^{N_{cnt}} \mathbf{f}_m - m\mathbf{g} \right\} \quad (4.312)$$

$$= m\ddot{\mathbf{c}} - \sum_{\substack{m=1 \\ m \in contact}}^{N_{cnt}} \mathbf{f}_m + m\mathbf{g} \in \mathbb{R}^3 \quad (4.313)$$

return $\bar{\mathbf{e}}^{eom-trans}(\mathbf{c}(t), \hat{\mathbf{w}}(t))$

:eom-trans-task-value $\mathcal{E}key$ ($update?$ t) [method]

$$\mathbf{e}^{eom-trans}(\mathbf{p}_c, \mathbf{p}_{\hat{w}}) = \begin{pmatrix} \bar{\mathbf{e}}^{eom-trans}(\mathbf{c}(t_1), \hat{\mathbf{w}}(t_1)) \\ \vdots \\ \bar{\mathbf{e}}^{eom-trans}(\mathbf{c}(t_{N_{tm-eom}}), \hat{\mathbf{w}}(t_{N_{tm-eom}})) \end{pmatrix} \in \mathbb{R}^{3N_{tm-eom}} \quad (4.314)$$

return $\mathbf{e}^{eom-trans}(\mathbf{p}_c, \mathbf{p}_{\hat{w}})$

:eom-rot-instant-task-value tm [method]

$$\bar{\mathbf{e}}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi) = \dot{\mathbf{L}} - \sum_{\substack{m=1 \\ m \in contact}}^{N_{cnt}} \{(\mathbf{p}_m^{cnt-trg}(\boldsymbol{\theta}, \phi) - \mathbf{c}) \times \mathbf{f}_m + \mathbf{n}_m\} \in \mathbb{R}^3 \quad (4.315)$$

return $\bar{\mathbf{e}}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi)$

:eom-rot-task-value $\mathcal{E}_{key} (update? t)$ [method]

$$\mathbf{e}^{eom-rot}(\mathbf{p}_{\theta}, \mathbf{p}_c, \mathbf{p}_L, \mathbf{p}_{\hat{w}}, \phi) = \begin{pmatrix} \bar{\mathbf{e}}^{eom-rot}(\boldsymbol{\theta}(t_1), \mathbf{c}(t_1), \mathbf{L}(t_1), \hat{\mathbf{w}}(t_1), \phi) \\ \vdots \\ \bar{\mathbf{e}}^{eom-rot}(\boldsymbol{\theta}(t_{N_{tm-eom}}), \mathbf{c}(t_{N_{tm-eom}}), \mathbf{L}(t_{N_{tm-eom}}), \hat{\mathbf{w}}(t_{N_{tm-eom}}), \phi) \end{pmatrix} \in \mathbb{R}^{3N_{tm-eom}} \quad (4.316)$$

return $\mathbf{e}^{eom-rot}(\mathbf{p}_{\theta}, \mathbf{p}_c, \mathbf{p}_L, \mathbf{p}_{\hat{w}}, \phi)$

:cog-instant-task-value tm [method]

$$\bar{\mathbf{e}}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \phi) = \mathbf{p}_G(\boldsymbol{\theta}, \phi) - \mathbf{c} \in \mathbb{R}^3 \quad (4.317)$$

return $\bar{\mathbf{e}}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \phi)$

:cog-task-value $\mathcal{E}_{key} (update? t)$ [method]

$$\mathbf{e}^{cog}(\mathbf{p}_{\theta}, \mathbf{p}_c, \phi) = \begin{pmatrix} \bar{\mathbf{e}}^{cog}(\boldsymbol{\theta}(t_1), \mathbf{c}(t_1), \phi) \\ \vdots \\ \bar{\mathbf{e}}^{cog}(\boldsymbol{\theta}(t_{N_{tm-eom}}), \mathbf{c}(t_{N_{tm-eom}}), \phi) \end{pmatrix} \in \mathbb{R}^{3N_{tm-eom}} \quad (4.318)$$

return $\mathbf{e}^{cog}(\mathbf{p}_{\theta}, \mathbf{p}_c, \phi)$

:ang-moment-instant-task-value tm [method]

$$\bar{\mathbf{e}}^{ang-moment}(\boldsymbol{\theta}(t), \mathbf{L}(t), \phi) = \mathbf{L}(t) - \left\{ \mathbf{A}_{\theta}(\boldsymbol{\theta}(t), \phi(t)) \dot{\boldsymbol{\theta}}(t) + \mathbf{A}_{\phi}(\boldsymbol{\theta}(t), \phi(t)) \dot{\phi}(t) \right\} \in \mathbb{R}^3 \quad (4.319)$$

本実装では, $\mathbf{A}_{\theta} = \mathbf{A}_{\phi} = \mathbf{O}$ という仮定を置く. このとき, タスク関数は次式となる.

$$\bar{\mathbf{e}}^{ang-moment}(\mathbf{L}(t)) = \mathbf{L}(t) \in \mathbb{R}^3 \quad (4.320)$$

return $\bar{\mathbf{e}}^{ang-moment}(\mathbf{L}(t))$

:ang-moment-task-value $\mathcal{E}_{key} (update? t)$ [method]

$$\mathbf{e}^{ang-moment}(\mathbf{p}_L) = \begin{pmatrix} \bar{\mathbf{e}}^{ang-moment}(\mathbf{L}(t_1)) \\ \vdots \\ \bar{\mathbf{e}}^{ang-moment}(\mathbf{L}(t_{N_{tm-com}})) \end{pmatrix} \in \mathbb{R}^{3N_{tm-com}} \quad (4.321)$$

return $\mathbf{e}^{ang-moment}(\mathbf{p}_L)$

:posture-instant-task-value tm [method]

$$\bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}(t)) = k_{posture}(\boldsymbol{\theta}_{posture}^{trg} - \boldsymbol{\theta}_{posture}) \in \mathbb{R}^{N_{posture-joint}} \quad (4.322)$$

$\boldsymbol{\theta}_{posture}^{trg}, \boldsymbol{\theta}_{posture}$ は着目関節リスト $\mathcal{J}_{posture}$ の目標関節角と現在の関節角 .

return $\bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}(t))$

:posture-task-value \mathcal{E}_{key} (update? t) [method]

$$\mathbf{e}^{posture}(\mathbf{p}_\theta) = \begin{pmatrix} \bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}(t_1)) \\ \vdots \\ \bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}(t_{N_{tm-kin}})) \end{pmatrix} \in \mathbb{R}^{N_{posture-joint} N_{tm-kin}} \quad (4.323)$$

return $\mathbf{e}^{posture}(\mathbf{p}_\theta)$

:task-value \mathcal{E}_{key} (update? t) [method]

$$\mathbf{e}(\mathbf{q}) = \begin{pmatrix} \mathbf{e}^{kin}(\mathbf{p}_\theta, \phi) \\ \mathbf{e}^{com-trans}(\mathbf{p}_c, \mathbf{p}_{\dot{w}}) \\ \mathbf{e}^{com-rot}(\mathbf{p}_\theta, \mathbf{p}_c, \mathbf{p}_L, \mathbf{p}_{\dot{w}}, \phi) \\ \mathbf{e}^{cog}(\mathbf{p}_\theta, \mathbf{p}_c, \phi) \\ \mathbf{e}^{ang-moment}(\mathbf{p}_\theta, \mathbf{p}_L, \phi) \\ \mathbf{e}^{trq}(\mathbf{p}_\theta, \mathbf{p}_{\dot{w}}, \mathbf{p}_\tau, \phi) \\ \mathbf{e}^{posture}(\mathbf{p}_\theta) \end{pmatrix} \quad (4.324)$$

return $\mathbf{e}(\mathbf{q}) \in \mathbb{R}^{dim(\mathbf{e})}$

:kinematics-instant-task-jacobian-with-theta-control-vector tm [method]

$$\frac{\partial \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t), \phi)}{\partial \mathbf{p}_\theta} = \frac{\partial \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t), \phi)}{\partial \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}(t)}{\partial \mathbf{p}_\theta} \quad (4.325)$$

$$\frac{\partial \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t), \phi)}{\partial \boldsymbol{\theta}} = \begin{pmatrix} \frac{\partial \bar{\mathbf{e}}_1^{kin}(\boldsymbol{\theta}(t), \phi)}{\partial \boldsymbol{\theta}} \\ \vdots \\ \frac{\partial \bar{\mathbf{e}}_{N_{kin}(t)}^{kin}(\boldsymbol{\theta}(t), \phi)}{\partial \boldsymbol{\theta}} \end{pmatrix} = \begin{pmatrix} \mathbf{J}_{1, \boldsymbol{\theta}(t)} \\ \vdots \\ \mathbf{J}_{N_{kin}(t), \boldsymbol{\theta}(t)} \end{pmatrix} \quad (4.326)$$

$$\frac{\partial \boldsymbol{\theta}(t)}{\partial \mathbf{p}_\theta} = \frac{\partial}{\partial \mathbf{p}_\theta} \mathbf{B}_{\theta, n}(t) \mathbf{p}_\theta = \mathbf{B}_{\theta, n}(t) \quad (4.327)$$

return $\frac{\partial \mathbf{e}^{kin}}{\partial \mathbf{p}_\theta} \in \mathbb{R}^{6N_{kin} \times dim(\mathbf{p}_\theta)}$

:kinematics-task-jacobian-with-theta-control-vector

[method]

$$\frac{\partial \mathbf{e}^{kin}}{\partial \mathbf{p}_\theta} = \begin{pmatrix} \frac{\partial \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t_1), \boldsymbol{\phi}(t_1))}{\partial \mathbf{p}_\theta} \\ \vdots \\ \frac{\partial \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t_{N_{tm-kin}}), \boldsymbol{\phi}(t_{N_{tm-kin}}))}{\partial \mathbf{p}_\theta} \end{pmatrix} \quad (4.328)$$

$$\text{return } \frac{\partial \mathbf{e}^{kin}}{\partial \mathbf{p}_\theta} \in \mathbb{R}^{6N_{kin} \times \dim(\mathbf{p}_\theta)}$$

:kinematics-instant-task-jacobian-with-phi tm

[method]

$$\frac{\partial \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t), \boldsymbol{\phi})}{\partial \boldsymbol{\phi}} = \frac{\partial \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t), \boldsymbol{\phi})}{\partial \boldsymbol{\phi}} \quad (4.329)$$

$$\frac{\partial \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t), \boldsymbol{\phi})}{\partial \boldsymbol{\phi}} = \begin{pmatrix} \frac{\partial \bar{\mathbf{e}}_1^{kin}(\boldsymbol{\theta}(t), \boldsymbol{\phi})}{\partial \boldsymbol{\phi}} \\ \vdots \\ \frac{\partial \bar{\mathbf{e}}_{N_{kin}(t)}^{kin}(\boldsymbol{\theta}(t), \boldsymbol{\phi})}{\partial \boldsymbol{\phi}} \end{pmatrix} = \begin{pmatrix} \mathbf{J}_{1,\boldsymbol{\phi}(t)} \\ \vdots \\ \mathbf{J}_{N_{kin}(t),\boldsymbol{\phi}(t)} \end{pmatrix} \quad (4.330)$$

$$\text{return } \frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\phi}} \in \mathbb{R}^{6N_{kin} \times \dim(\boldsymbol{\phi})}$$

:kinematics-task-jacobian-with-phi

[method]

$$\frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\phi}} = \begin{pmatrix} \frac{\partial \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t_1), \boldsymbol{\phi}(t_1))}{\partial \boldsymbol{\phi}} \\ \vdots \\ \frac{\partial \bar{\mathbf{e}}^{kin}(\boldsymbol{\theta}(t_{N_{tm-kin}}), \boldsymbol{\phi}(t_{N_{tm-kin}}))}{\partial \boldsymbol{\phi}} \end{pmatrix} \quad (4.331)$$

$$\text{return } \frac{\partial \mathbf{e}^{kin}}{\partial \boldsymbol{\phi}} \in \mathbb{R}^{6N_{kin} \times \dim(\boldsymbol{\phi})}$$

:eom-trans-instant-task-jacobian-with-cog-control-vector tm

[method]

$$\frac{\partial \bar{\mathbf{e}}^{eom-trans}(\mathbf{c}(t), \hat{\mathbf{w}}(t))}{\partial \mathbf{p}_c} = m \frac{\partial \check{\mathbf{c}}(t)}{\partial \mathbf{p}_c} \quad (4.332)$$

$$= m \frac{\partial}{\partial \mathbf{p}_c} \mathbf{B}_{c,n-2}(t) \hat{\mathbf{D}}_2 \mathbf{p}_c \quad (4.333)$$

$$= m \mathbf{B}_{c,n-2}(t) \hat{\mathbf{D}}_2 \quad (4.334)$$

$$\text{return } \frac{\partial \bar{\mathbf{e}}^{eom-trans}(\mathbf{c}(t), \hat{\mathbf{w}}(t))}{\partial \mathbf{p}_c} \in \mathbb{R}^{3 \times \dim(\mathbf{p}_c)}$$

:eom-trans-task-jacobian-with-cog-control-vector

[method]

$$\frac{\partial \mathbf{e}^{eom-trans}}{\partial \mathbf{p}_c} = \begin{pmatrix} \frac{\partial \bar{\mathbf{e}}^{eom-trans}(\mathbf{c}(t_1), \hat{\mathbf{w}}(t_1))}{\partial \mathbf{p}_c} \\ \vdots \\ \frac{\partial \bar{\mathbf{e}}^{eom-trans}(\mathbf{c}(t_{N_{tm-eom}}), \hat{\mathbf{w}}(t_{N_{tm-eom}}))}{\partial \mathbf{p}_c} \end{pmatrix} \quad (4.335)$$

$$\text{return } \frac{\partial \mathbf{e}^{eom-trans}}{\partial \mathbf{p}_c} \in \mathbb{R}^{3N_{tm-eom} \times \dim(\mathbf{p}_c)}$$

:eom-trans-instant-task-jacobian-with-wrench-control-vector tm

[method]

$$\frac{\partial \bar{e}^{eom-trans}(c(t), \hat{w}(t))}{\partial \mathbf{p}_{\hat{w}}} = \frac{\partial \bar{e}^{eom-trans}(c(t), \hat{w}(t))}{\partial \hat{w}} \frac{\partial \hat{w}(t)}{\partial \mathbf{p}_{\hat{w}}} \quad (4.336)$$

$$\frac{\partial \bar{e}^{eom-trans}(c(t), \hat{w}(t))}{\partial \hat{w}} = \begin{pmatrix} -I_3 & O_3 & \cdots & -I_3 & O_3 \end{pmatrix} \quad (4.337)$$

(ただし, $\mathbf{p}_m^{cnt-trg}$ が nil の接触については, O_3 とする)

$$\frac{\partial \hat{w}(t)}{\partial \mathbf{p}_{\hat{w}}} = \frac{\partial}{\partial \mathbf{p}_{\hat{w}}} B_{\hat{w},n}(t) \mathbf{p}_{\hat{w}} = B_{\hat{w},n}(t) \quad (4.338)$$

$$\text{return } \frac{\partial \bar{e}^{eom-trans}(c(t), \hat{w}(t))}{\partial \mathbf{p}_{\hat{w}}} \in \mathbb{R}^{3 \times \dim(\mathbf{p}_{\hat{w}})}$$

:eom-trans-task-jacobian-with-wrench-control-vector

[method]

$$\frac{\partial e^{eom-trans}}{\partial \mathbf{p}_{\hat{w}}} = \begin{pmatrix} \frac{\partial \bar{e}^{eom-trans}(c(t_1), \hat{w}(t_1))}{\partial \mathbf{p}_{\hat{w}}} \\ \vdots \\ \frac{\partial \bar{e}^{eom-trans}(c(t_{N_{tm-eom}}), \hat{w}(t_{N_{tm-eom}}))}{\partial \mathbf{p}_{\hat{w}}} \end{pmatrix} \quad (4.339)$$

$$\text{return } \frac{\partial e^{eom-trans}}{\partial \mathbf{p}_{\hat{w}}} \in \mathbb{R}^{3N_{tm-eom} \times \dim(\mathbf{p}_{\hat{w}})}$$

:eom-rot-instant-task-jacobian-with-theta-control-vector tm

[method]

$$\frac{\partial \bar{e}^{eom-rot}(\theta(t), c(t), L(t), \hat{w}(t), \phi)}{\partial \mathbf{p}_{\theta}} = \frac{\partial \bar{e}^{eom-rot}(\theta(t), c(t), L(t), \hat{w}(t), \phi)}{\partial \theta} \frac{\partial \theta(t)}{\partial \mathbf{p}_{\theta}} \quad (4.340)$$

$$\frac{\partial \bar{e}^{eom-rot}(\theta(t), c(t), L(t), \hat{w}(t), \phi)}{\partial \theta} = \sum_{\substack{m=1 \\ m \in \text{contact}}}^{N_{cnt}} \left\{ [\mathbf{f}_m(t) \times] \mathbf{J}_{m,\theta}^{cnt-trg}(t) \right\} \quad (4.341)$$

$$\frac{\partial \theta(t)}{\partial \mathbf{p}_{\theta}} = \frac{\partial}{\partial \mathbf{p}_{\theta}} B_{\theta,n}(t) \mathbf{p}_{\theta} = B_{\theta,n}(t) \quad (4.342)$$

$$\text{return } \frac{\partial \bar{e}^{eom-rot}(\theta(t), c(t), L(t), \hat{w}(t), \phi)}{\partial \mathbf{p}_{\theta}} \in \mathbb{R}^{3 \times \dim(\mathbf{p}_{\theta})}$$

:eom-rot-task-jacobian-with-theta-control-vector

[method]

$$\frac{\partial e^{eom-rot}}{\partial \mathbf{p}_{\theta}} = \begin{pmatrix} \frac{\partial \bar{e}^{eom-rot}(\theta(t_1), c(t_1), L(t_1), \hat{w}(t_1), \phi)}{\partial \mathbf{p}_{\theta}} \\ \vdots \\ \frac{\partial \bar{e}^{eom-rot}(\theta(t_{N_{tm-eom}}), c(t_{N_{tm-eom}}), L(t_{N_{tm-eom}}), \hat{w}(t_{N_{tm-eom}}), \phi)}{\partial \mathbf{p}_{\theta}} \end{pmatrix} \quad (4.343)$$

$$\text{return } \frac{\partial e^{eom-rot}}{\partial \mathbf{p}_{\theta}} \in \mathbb{R}^{3N_{tm-eom} \times \dim(\mathbf{p}_{\theta})}$$

:eom-rot-instant-task-jacobian-with-cog-control-vector tm

[method]

$$\frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi)}{\partial \mathbf{p}_c} = \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi)}{\partial \mathbf{c}} \frac{\partial \mathbf{c}(t)}{\partial \mathbf{p}_c} \quad (4.344)$$

$$\frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi)}{\partial \mathbf{c}} = - \sum_{\substack{m=1 \\ m \in \text{contact}}}^{N_{cnt}} [\mathbf{f}_m \times] = \left[\left(- \sum_{\substack{m=1 \\ m \in \text{contact}}}^{N_{cnt}} \mathbf{f}_m \right) \times \right] \quad (4.345)$$

$$\frac{\partial \mathbf{c}(t)}{\partial \mathbf{p}_c} = \frac{\partial}{\partial \mathbf{p}_c} \mathbf{B}_{c,n}(t) \mathbf{p}_c = \mathbf{B}_{c,n}(t) \quad (4.346)$$

$$\text{return } \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi)}{\partial \mathbf{p}_c} \in \mathbb{R}^{3 \times \dim(\mathbf{p}_c)}$$

:eom-rot-task-jacobian-with-cog-control-vector

[method]

$$\frac{\partial \bar{e}^{eom-rot}}{\partial \mathbf{p}_c} = \begin{pmatrix} \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t_1), \mathbf{c}(t_1), \mathbf{L}(t_1), \hat{\mathbf{w}}(t_1), \phi)}{\partial \mathbf{p}_c} \\ \vdots \\ \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t_{N_{tm-eom}}), \mathbf{c}(t_{N_{tm-eom}}), \mathbf{L}(t_{N_{tm-eom}}), \hat{\mathbf{w}}(t_{N_{tm-eom}}), \phi)}{\partial \mathbf{p}_c} \end{pmatrix} \quad (4.347)$$

$$\text{return } \frac{\partial \bar{e}^{eom-rot}}{\partial \mathbf{p}_c} \in \mathbb{R}^{3N_{tm-eom} \times \dim(\mathbf{p}_c)}$$

:eom-rot-instant-task-jacobian-with-ang-moment-control-vector tm

[method]

$$\frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi)}{\partial \mathbf{p}_L} = \frac{\partial \dot{\mathbf{L}}(t)}{\partial \mathbf{p}_L} \quad (4.348)$$

$$= \frac{\partial}{\partial \mathbf{p}_L} \mathbf{B}_{L,n-1}(t) \hat{\mathbf{D}}_1 \mathbf{p}_L \quad (4.349)$$

$$= \mathbf{B}_{L,n-1}(t) \hat{\mathbf{D}}_1 \quad (4.350)$$

$$\text{return } \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi)}{\partial \mathbf{p}_L} \in \mathbb{R}^{3 \times \dim(\mathbf{p}_L)}$$

:eom-rot-task-jacobian-with-ang-moment-control-vector

[method]

$$\frac{\partial \bar{e}^{eom-rot}}{\partial \mathbf{p}_L} = \begin{pmatrix} \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t_1), \mathbf{c}(t_1), \mathbf{L}(t_1), \hat{\mathbf{w}}(t_1), \phi)}{\partial \mathbf{p}_L} \\ \vdots \\ \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t_{N_{tm-eom}}), \mathbf{c}(t_{N_{tm-eom}}), \mathbf{L}(t_{N_{tm-eom}}), \hat{\mathbf{w}}(t_{N_{tm-eom}}), \phi)}{\partial \mathbf{p}_L} \end{pmatrix} \quad (4.351)$$

$$\text{return } \frac{\partial \bar{e}^{eom-rot}}{\partial \mathbf{p}_L} \in \mathbb{R}^{3N_{tm-eom} \times \dim(\mathbf{p}_L)}$$

:eom-rot-instant-task-jacobian-with-wrench-control-vector tm

[method]

$$\frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi)}{\partial \mathbf{p}_{\hat{\mathbf{w}}}} = \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi)}{\partial \hat{\mathbf{w}}} \frac{\partial \hat{\mathbf{w}}(t)}{\partial \mathbf{p}_{\hat{\mathbf{w}}}} \quad (4.352)$$

$$\frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \phi)}{\partial \hat{\mathbf{w}}} = \left(\left[-(\mathbf{p}_1^{cnt-trg}(\boldsymbol{\theta}, \phi) - \mathbf{c}) \times \right] \quad -\mathbf{I}_3 \quad \cdots \quad \left[-(\mathbf{p}_{N_{cnt}}^{cnt-trg}(\boldsymbol{\theta}, \phi) - \mathbf{c}) \times \right] \right) \quad (4.353)$$

(ただし, $\mathbf{p}_m^{cnt-trg}$ が nil の接触については, \mathbf{O}_3 とする)

$$\frac{\partial \hat{\mathbf{w}}(t)}{\partial \mathbf{p}_{\hat{\mathbf{w}}}} = \frac{\partial}{\partial \mathbf{p}_{\hat{\mathbf{w}}}} \mathbf{B}_{\hat{\mathbf{w}},n}(t) \mathbf{p}_{\hat{\mathbf{w}}} = \mathbf{B}_{\hat{\mathbf{w}},n}(t) \quad (4.354)$$

$$\text{return } \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \boldsymbol{\phi})}{\partial \mathbf{p}_{\hat{\mathbf{w}}}} \in \mathbb{R}^{3 \times \dim(\mathbf{p}_{\hat{\mathbf{w}}})}$$

:eom-rot-task-jacobian-with-wrench-control-vector

[method]

$$\frac{\partial \mathbf{e}^{eom-rot}}{\partial \mathbf{p}_{\hat{\mathbf{w}}}} = \begin{pmatrix} \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t_1), \mathbf{c}(t_1), \mathbf{L}(t_1), \hat{\mathbf{w}}(t_1), \boldsymbol{\phi})}{\partial \mathbf{p}_{\hat{\mathbf{w}}}} \\ \vdots \\ \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t_{N_{tm-eom}}), \mathbf{c}(t_{N_{tm-eom}}), \mathbf{L}(t_{N_{tm-eom}}), \hat{\mathbf{w}}(t_{N_{tm-eom}}), \boldsymbol{\phi})}{\partial \mathbf{p}_{\hat{\mathbf{w}}}} \end{pmatrix} \quad (4.355)$$

$$\text{return } \frac{\partial \mathbf{e}^{eom-rot}}{\partial \mathbf{p}_{\hat{\mathbf{w}}}} \in \mathbb{R}^{3N_{tm-eom} \times \dim(\mathbf{p}_{\hat{\mathbf{w}}})}$$

:eom-rot-instant-task-jacobian-with-phi tm

[method]

$$\frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \boldsymbol{\phi})}{\partial \boldsymbol{\phi}} = \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \boldsymbol{\phi})}{\partial \boldsymbol{\phi}} \quad (4.356)$$

$$= \sum_{\substack{m=1 \\ m \in \text{contact}}}^{N_{cnt}} \left\{ [\mathbf{f}_m(t) \times] \mathbf{J}_{m,\phi}^{cnt-trg}(t) \right\} \quad (4.357)$$

$$\text{return } \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t), \mathbf{c}(t), \mathbf{L}(t), \hat{\mathbf{w}}(t), \boldsymbol{\phi})}{\partial \boldsymbol{\phi}} \in \mathbb{R}^{3 \times \dim(\boldsymbol{\phi})}$$

:eom-rot-task-jacobian-with-phi

[method]

$$\frac{\partial \mathbf{e}^{eom-rot}}{\partial \boldsymbol{\phi}} = \begin{pmatrix} \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t_1), \mathbf{c}(t_1), \mathbf{L}(t_1), \hat{\mathbf{w}}(t_1), \boldsymbol{\phi})}{\partial \boldsymbol{\phi}} \\ \vdots \\ \frac{\partial \bar{e}^{eom-rot}(\boldsymbol{\theta}(t_{N_{tm-eom}}), \mathbf{c}(t_{N_{tm-eom}}), \mathbf{L}(t_{N_{tm-eom}}), \hat{\mathbf{w}}(t_{N_{tm-eom}}), \boldsymbol{\phi})}{\partial \boldsymbol{\phi}} \end{pmatrix} \quad (4.358)$$

$$\text{return } \frac{\partial \mathbf{e}^{eom-rot}}{\partial \boldsymbol{\phi}} \in \mathbb{R}^{3N_{tm-eom} \times \dim(\boldsymbol{\phi})}$$

:cog-instant-task-jacobian-with-theta-control-vector tm

[method]

$$\frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \boldsymbol{\phi})}{\partial \mathbf{p}_{\boldsymbol{\theta}}} = \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \boldsymbol{\phi})}{\partial \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}(t)}{\partial \mathbf{p}_{\boldsymbol{\theta}}} \quad (4.359)$$

$$\frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \boldsymbol{\phi})}{\partial \boldsymbol{\theta}} = \mathbf{J}_{G,\theta}(t) \quad (4.360)$$

$$\frac{\partial \boldsymbol{\theta}(t)}{\partial \mathbf{p}_{\boldsymbol{\theta}}} = \frac{\partial}{\partial \mathbf{p}_{\boldsymbol{\theta}}} \mathbf{B}_{\theta,n}(t) \mathbf{p}_{\boldsymbol{\theta}} = \mathbf{B}_{\theta,n}(t) \quad (4.361)$$

$$\text{return } \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \boldsymbol{\phi})}{\partial \mathbf{p}_{\boldsymbol{\theta}}} \in \mathbb{R}^{3 \times \dim(\mathbf{p}_{\boldsymbol{\theta}})}$$

:cog-task-jacobian-with-theta-control-vector

[method]

$$\frac{\partial \mathbf{e}^{cog}}{\partial \mathbf{p}_{\boldsymbol{\theta}}} = \begin{pmatrix} \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t_1), \mathbf{c}(t_1), \boldsymbol{\phi})}{\partial \mathbf{p}_{\boldsymbol{\theta}}} \\ \vdots \\ \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t_{N_{tm-eom}}), \mathbf{c}(t_{N_{tm-eom}}), \boldsymbol{\phi})}{\partial \mathbf{p}_{\boldsymbol{\theta}}} \end{pmatrix} \quad (4.362)$$

$$\text{return } \frac{\partial \mathbf{e}^{cog}}{\partial \mathbf{p}_{\boldsymbol{\theta}}} \in \mathbb{R}^{3N_{tm-eom} \times \dim(\mathbf{p}_{\boldsymbol{\theta}})}$$

:cog-instant-task-jacobian-with-cog-control-vector tm

[method]

$$\frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \phi)}{\partial \mathbf{p}_c} = \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \phi)}{\partial \mathbf{c}} \frac{\partial \mathbf{c}(t)}{\partial \mathbf{p}_c} \quad (4.363)$$

$$\frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \phi)}{\partial \mathbf{c}} = -\mathbf{I}_3 \quad (4.364)$$

$$\frac{\partial \mathbf{c}(t)}{\partial \mathbf{p}_c} = \frac{\partial}{\partial \mathbf{p}_c} \mathbf{B}_{c,n}(t) \mathbf{p}_c = \mathbf{B}_{c,n}(t) \quad (4.365)$$

$$\text{return } \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \phi)}{\partial \mathbf{p}_c} \in \mathbb{R}^{3 \times \dim(\mathbf{p}_c)}$$

:cog-task-jacobian-with-cog-control-vector

[method]

$$\frac{\partial \mathbf{e}^{cog}}{\partial \mathbf{p}_c} = \begin{pmatrix} \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t_1), \mathbf{c}(t_1), \phi)}{\partial \mathbf{p}_c} \\ \vdots \\ \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t_{N_{tm-com}}), \mathbf{c}(t_{N_{tm-com}}), \phi)}{\partial \mathbf{p}_c} \end{pmatrix} \quad (4.366)$$

$$\text{return } \frac{\partial \mathbf{e}^{cog}}{\partial \mathbf{p}_c} \in \mathbb{R}^{3N_{tm-com} \times \dim(\mathbf{p}_c)}$$

:cog-instant-task-jacobian-with-phi tm

[method]

$$\frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \phi)}{\partial \phi} = \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \phi)}{\partial \phi} = \mathbf{J}_{G,\phi}(t) \quad (4.367)$$

$$\text{return } \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t), \mathbf{c}(t), \phi)}{\partial \phi} \in \mathbb{R}^{3 \times \dim(\phi)}$$

:cog-task-jacobian-with-phi

[method]

$$\frac{\partial \mathbf{e}^{cog}}{\partial \phi} = \begin{pmatrix} \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t_1), \mathbf{c}(t_1), \phi)}{\partial \phi} \\ \vdots \\ \frac{\partial \bar{e}^{cog}(\boldsymbol{\theta}(t_{N_{tm-com}}), \mathbf{c}(t_{N_{tm-com}}), \phi)}{\partial \phi} \end{pmatrix} \quad (4.368)$$

$$\text{return } \frac{\partial \mathbf{e}^{cog}}{\partial \phi} \in \mathbb{R}^{3N_{tm-com} \times \dim(\phi)}$$

:ang-moment-instant-task-jacobian-with-ang-moment-control-vector tm

[method]

$$\frac{\partial \bar{e}^{ang-moment}(\mathbf{L}(t))}{\partial \mathbf{p}_L} = \frac{\partial \bar{e}^{ang-moment}(\mathbf{L}(t))}{\partial \mathbf{L}} \frac{\partial \mathbf{L}(t)}{\partial \mathbf{p}_L} \quad (4.369)$$

$$\frac{\partial \bar{e}^{ang-moment}(\mathbf{L}(t))}{\partial \mathbf{L}} = \mathbf{I}_3 \quad (4.370)$$

$$\frac{\partial \mathbf{L}(t)}{\partial \mathbf{p}_L} = \frac{\partial}{\partial \mathbf{p}_L} \mathbf{B}_{L,n}(t) \mathbf{p}_L = \mathbf{B}_{L,n}(t) \quad (4.371)$$

$$\text{return } \frac{\partial \bar{e}^{ang-moment}(\mathbf{L}(t))}{\partial \mathbf{p}_L} \in \mathbb{R}^{3 \times \dim(\mathbf{p}_L)}$$

:ang-moment-task-jacobian-with-ang-moment-control-vector

[method]

$$\frac{\partial \mathbf{e}^{ang-moment}}{\partial \mathbf{p}_L} = \begin{pmatrix} \frac{\partial \bar{\mathbf{e}}^{ang-moment}(\mathbf{L}(t_1))}{\partial \mathbf{p}_L} \\ \vdots \\ \frac{\partial \bar{\mathbf{e}}^{ang-moment}(\mathbf{L}(t_{N_{tm-com}}))}{\partial \mathbf{p}_L} \end{pmatrix} \quad (4.372)$$

$$\text{return } \frac{\partial \mathbf{e}^{ang-moment}}{\partial \mathbf{p}_L} \in \mathbb{R}^{3N_{tm-com} \times \dim(\mathbf{p}_L)}$$

:posture-instant-task-jacobian-with-theta-control-vector *tm* [method]

$$\frac{\partial \bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}(t))}{\partial \mathbf{p}_\theta} = \frac{\partial \bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}(t))}{\partial \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}(t)}{\partial \mathbf{p}_\theta} \quad (4.373)$$

$$\left(\frac{\partial \bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}(t))}{\partial \boldsymbol{\theta}} \right)_{i,j} = \begin{cases} -k_{posture} & (\mathcal{J}_{posture,i} = \mathcal{J}_{var,j}) \\ 0 & \text{otherwise} \end{cases} \quad (4.374)$$

$$\frac{\partial \boldsymbol{\theta}(t)}{\partial \mathbf{p}_\theta} = \frac{\partial}{\partial \mathbf{p}_\theta} \mathbf{B}_{\theta,n}(t) \mathbf{p}_\theta = \mathbf{B}_{\theta,n}(t) \quad (4.375)$$

$$\text{return } \frac{\partial \bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}(t))}{\partial \mathbf{p}_\theta} \in \mathbb{R}^{N_{posture-joint} \times \dim(\mathbf{p}_\theta)}$$

:posture-task-jacobian-with-theta-control-vector [method]

$$\frac{\partial \mathbf{e}^{posture}}{\partial \mathbf{p}_\theta} = \begin{pmatrix} \frac{\partial \bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}(t_1))}{\partial \mathbf{p}_\theta} \\ \vdots \\ \frac{\partial \bar{\mathbf{e}}^{posture}(\boldsymbol{\theta}(t_{N_{tm-kin}}))}{\partial \mathbf{p}_\theta} \end{pmatrix} \quad (4.376)$$

$$\text{return } \frac{\partial \mathbf{e}^{posture}}{\partial \mathbf{p}_\theta} \in \mathbb{R}^{N_{posture-joint} N_{tm-kin} \times \dim(\mathbf{p}_\theta)}$$

:task-jacobian [method]

$$\frac{\partial \mathbf{e}}{\partial \mathbf{q}} = \begin{matrix} \begin{matrix} \dim(\mathbf{e}^{kin}(\mathbf{p}_\theta, \phi)) \\ \dim(\mathbf{e}^{com-trans}(\mathbf{p}_c, \mathbf{p}_{\dot{w}})) \\ \dim(\mathbf{e}^{com-rot}(\mathbf{p}_\theta, \mathbf{p}_c, \mathbf{p}_L, \mathbf{p}_{\dot{w}}, \phi)) \\ \dim(\mathbf{e}^{cog}(\mathbf{p}_\theta, \mathbf{p}_c, \phi)) \\ \dim(\mathbf{e}^{ang-moment}(\mathbf{p}_\theta, \mathbf{p}_L, \phi)) \\ \dim(\mathbf{e}^{trq}(\mathbf{p}_\theta, \mathbf{p}_{\dot{w}}, \mathbf{p}_\tau, \phi)) \\ \dim(\mathbf{e}^{posture}(\mathbf{p}_\theta)) \end{matrix} & \begin{pmatrix} \begin{matrix} \dim(\mathbf{p}_\theta) & \dim(\mathbf{p}_c) & \dim(\mathbf{p}_L) & \dim(\mathbf{p}_{\dot{w}}) & \dim(\mathbf{p}_\tau) & \dim(\phi) \end{matrix} \\ \frac{\partial \mathbf{e}^{kin}}{\partial \mathbf{p}_\theta} & & & & & \frac{\partial \mathbf{e}^{kin}}{\partial \phi} \\ & \frac{\partial \mathbf{e}^{com-trans}}{\partial \mathbf{p}_c} & & \frac{\partial \mathbf{e}^{com-trans}}{\partial \mathbf{p}_{\dot{w}}} & & \\ \frac{\partial \mathbf{e}^{com-rot}}{\partial \mathbf{p}_\theta} & \frac{\partial \mathbf{e}^{com-rot}}{\partial \mathbf{p}_c} & \frac{\partial \mathbf{e}^{com-rot}}{\partial \mathbf{p}_L} & \frac{\partial \mathbf{e}^{com-rot}}{\partial \mathbf{p}_{\dot{w}}} & & \frac{\partial \mathbf{e}^{com-rot}}{\partial \phi} \\ \frac{\partial \mathbf{e}^{cog}}{\partial \mathbf{p}_\theta} & \frac{\partial \mathbf{e}^{cog}}{\partial \mathbf{p}_c} & & & & \frac{\partial \mathbf{e}^{cog}}{\partial \phi} \\ & & \frac{\partial \mathbf{e}^{ang-moment}}{\partial \mathbf{p}_L} & & & \\ \frac{\partial \mathbf{e}^{posture}}{\partial \mathbf{p}_\theta} & & & & & \end{pmatrix} \end{pmatrix} \quad (4.377)$$

$$\text{return } \frac{\partial \mathbf{e}}{\partial \mathbf{q}} = \mathbb{R}^{\dim(\mathbf{e}) \times \dim(\mathbf{q})}$$

:theta-max-vector *ℰkey (update? nil)* [method]

$$\text{return } \boldsymbol{\theta}_{max} \in \mathbb{R}^{N_{var-joint}}$$

:theta-min-vector *ℰkey (update? nil)* [method]

$$\text{return } \boldsymbol{\theta}_{min} \in \mathbb{R}^{N_{var-joint}}$$

:theta-instant-inequality-constraint-matrix *ℰkey (update? nil)* [method]

$$\boldsymbol{\theta}_{min} \leq \boldsymbol{\theta} \leq \boldsymbol{\theta}_{max} \quad (4.378)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \boldsymbol{\theta} \geq \begin{pmatrix} \boldsymbol{\theta}_{min} \\ -\boldsymbol{\theta}_{max} \end{pmatrix} \quad (4.379)$$

$$\Leftrightarrow \mathbf{C}_{\boldsymbol{\theta}} \boldsymbol{\theta} \geq \bar{\mathbf{d}}_{\boldsymbol{\theta}} \quad (4.380)$$

$$\text{return } \mathbf{C}_{\boldsymbol{\theta}} := \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \in \mathbb{R}^{2N_{var-joint} \times N_{var-joint}}$$

:theta-instant-inequality-constraint-vector *ℰkey (update? nil)* [method]

$$\text{return } \bar{\mathbf{d}}_{\boldsymbol{\theta}} := \begin{pmatrix} \boldsymbol{\theta}_{min} \\ -\boldsymbol{\theta}_{max} \end{pmatrix} \in \mathbb{R}^{2N_{var-joint}}$$

:theta-control-vector-inequality-constraint-matrix *ℰkey (update? nil)* [method]

$$\mathbf{C}_{\boldsymbol{\theta}} \boldsymbol{\theta} \geq \bar{\mathbf{d}}_{\boldsymbol{\theta}} \quad (4.381)$$

$$\Leftrightarrow \mathbf{C}_{\mathbf{p}_{\boldsymbol{\theta}}} \mathbf{p}_{\boldsymbol{\theta}} \geq \bar{\mathbf{d}}_{\mathbf{p}_{\boldsymbol{\theta}}} \quad (4.382)$$

差分形式で表すと次式となる .

$$\mathbf{C}_{\mathbf{p}_{\boldsymbol{\theta}}} (\mathbf{p}_{\boldsymbol{\theta}} + \Delta \mathbf{p}_{\boldsymbol{\theta}}) \geq \bar{\mathbf{d}}_{\mathbf{p}_{\boldsymbol{\theta}}} \quad (4.383)$$

$$\Leftrightarrow \mathbf{C}_{\mathbf{p}_{\boldsymbol{\theta}}} \Delta \mathbf{p}_{\boldsymbol{\theta}} \geq \bar{\mathbf{d}}_{\mathbf{p}_{\boldsymbol{\theta}}} - \mathbf{C}_{\mathbf{p}_{\boldsymbol{\theta}}} \mathbf{p}_{\boldsymbol{\theta}} \quad (4.384)$$

$$\Leftrightarrow \mathbf{C}_{\mathbf{p}_{\boldsymbol{\theta}}} \Delta \mathbf{p}_{\boldsymbol{\theta}} \geq \mathbf{d}_{\mathbf{p}_{\boldsymbol{\theta}}} \quad (4.385)$$

$$\text{return } \mathbf{C}_{\mathbf{p}_{\boldsymbol{\theta}}}$$

:theta-control-vector-inequality-constraint-vector *ℰkey (update? t)* [method]

$$\text{return } \mathbf{d}_{\mathbf{p}_{\boldsymbol{\theta}}} := \bar{\mathbf{d}}_{\mathbf{p}_{\boldsymbol{\theta}}} - \mathbf{C}_{\mathbf{p}_{\boldsymbol{\theta}}} \mathbf{p}_{\boldsymbol{\theta}}$$

:cog-max-vector *ℰkey (update? nil)* [method]

$$\text{return } \mathbf{c}_{max} \in \mathbb{R}^3 \text{ [m]}$$

:cog-instant-inequality-constraint-matrix *ℰkey (update? nil)* [method]

$$-\mathbf{c}_{max} \leq \mathbf{c} \leq \mathbf{c}_{max} \quad (4.386)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \mathbf{c} \geq \begin{pmatrix} -\mathbf{c}_{max} \\ -\mathbf{c}_{max} \end{pmatrix} \quad (4.387)$$

$$\Leftrightarrow \mathbf{C}_{\mathbf{c}} \mathbf{c} \geq \bar{\mathbf{d}}_{\mathbf{c}} \quad (4.388)$$

$$\text{return } \mathbf{C}_{\mathbf{c}} := \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \in \mathbb{R}^{6 \times 3}$$

:cog-instant-inequality-constraint-vector *ℰkey (update? nil)* [method]

$$\text{return } \bar{\mathbf{d}}_{\mathbf{c}} := \begin{pmatrix} -\mathbf{c}_{max} \\ -\mathbf{c}_{max} \end{pmatrix} \in \mathbb{R}^6$$

:cog-control-vector-inequality-constraint-matrix *ℰkey (update? nil)* [method]

$$C_c c \geq \bar{d}_c \quad (4.389)$$

$$\Leftrightarrow C_{p_c} p_c \geq \bar{d}_{p_c} \quad (4.390)$$

差分形式で表すと次式となる .

$$C_{p_c} (p_c + \Delta p_c) \geq \bar{d}_{p_c} \quad (4.391)$$

$$\Leftrightarrow C_{p_c} \Delta p_c \geq \bar{d}_{p_c} - C_{p_c} p_c \quad (4.392)$$

$$\Leftrightarrow C_{p_c} \Delta p_c \geq d_{p_c} \quad (4.393)$$

return C_{p_c}

:cog-control-vector-inequality-constraint-vector $\mathcal{E}key$ (*update?* *t*) [method]

return $d_{p_c} := \bar{d}_{p_c} - C_{p_c} p_c$

:ang-moment-max-vector $\mathcal{E}key$ (*update?* *nil*) [method]

return $L_{max} \in \mathbb{R}^3$ [kgm²/s]

:ang-moment-instant-inequality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]

$$-L_{max} \leq L \leq L_{max} \quad (4.394)$$

$$\Leftrightarrow \begin{pmatrix} I \\ -I \end{pmatrix} L \geq \begin{pmatrix} -L_{max} \\ -L_{max} \end{pmatrix} \quad (4.395)$$

$$\Leftrightarrow C_L L \geq \bar{d}_L \quad (4.396)$$

return $C_L := \begin{pmatrix} I \\ -I \end{pmatrix} \in \mathbb{R}^{6 \times 3}$

:ang-moment-instant-inequality-constraint-vector $\mathcal{E}key$ (*update?* *nil*) [method]

return $\bar{d}_L := \begin{pmatrix} -L_{max} \\ -L_{max} \end{pmatrix} \in \mathbb{R}^6$

:ang-moment-control-vector-inequality-constraint-matrix $\mathcal{E}key$ (*update?* *nil*) [method]

$$C_L L \geq \bar{d}_L \quad (4.397)$$

$$\Leftrightarrow C_{p_L} p_L \geq \bar{d}_{p_L} \quad (4.398)$$

差分形式で表すと次式となる .

$$C_{p_L} (p_L + \Delta p_L) \geq \bar{d}_{p_L} \quad (4.399)$$

$$\Leftrightarrow C_{p_L} \Delta p_L \geq \bar{d}_{p_L} - C_{p_L} p_L \quad (4.400)$$

$$\Leftrightarrow C_{p_L} \Delta p_L \geq d_{p_L} \quad (4.401)$$

return C_{p_L}

:ang-moment-control-vector-inequality-constraint-vector $\mathcal{E}key$ (*update?* *t*) [method]

return $d_{p_L} := \bar{d}_{p_L} - C_{p_L} p_L$

:wrench-instant-inequality-constraint-matrix $\mathcal{E}key$ (*update?* *t*) [method]

接触レンチ $w \in \mathbb{R}^6$ が満たすべき制約（非負制約，摩擦制約，圧力中心制約）が次式のように表されるとする．

$$C_w w \geq d_w \quad (4.402)$$

N_{cnt} 箇所の接触部位の接触レンチを並べたベクトル \hat{w} の不等式制約は次式で表される．

$$C_{w,m} w_m \geq d_{w,m} \quad (m = 1, 2, \dots, N_{cnt}) \quad (4.403)$$

$$\Leftrightarrow \begin{pmatrix} C_{w,1} & & & \\ & C_{w,2} & & \\ & & \ddots & \\ & & & C_{w,N_{cnt}} \end{pmatrix} \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_{N_{cnt}} \end{pmatrix} \geq \begin{pmatrix} d_{w,1} \\ d_{w,2} \\ \vdots \\ d_{w,N_{cnt}} \end{pmatrix} \quad (4.404)$$

$$\Leftrightarrow C_{\hat{w}} \hat{w} \geq d_{\hat{w}} \quad (4.405)$$

$$\text{return } C_{\hat{w}} := \begin{pmatrix} C_{w,1} & & & \\ & C_{w,2} & & \\ & & \ddots & \\ & & & C_{w,N_{cnt}} \end{pmatrix} \in \mathbb{R}^{N_{\hat{w}-ineq} \times \dim(\hat{w})}$$

:wrench-instant-inequality-constraint-vector *ℰkey (update? nil)* [method]

$$\text{return } d_{\hat{w}} := \begin{pmatrix} d_{w,1} \\ d_{w,2} \\ \vdots \\ d_{w,N_{cnt}} \end{pmatrix} \in \mathbb{R}^{N_{\hat{w}-ineq}}$$

:wrench-control-vector-inequality-constraint-matrix *ℰkey (update? nil)* [method]

$$C_{\hat{w}} \hat{w} \geq \bar{d}_{\hat{w}} \quad (4.406)$$

$$\Leftrightarrow C_{p_{\hat{w}}} p_{\hat{w}} \geq \bar{d}_{p_{\hat{w}}} \quad (4.407)$$

差分形式で表すと次式となる．

$$C_{p_{\hat{w}}} (p_{\hat{w}} + \Delta p_{\hat{w}}) \geq \bar{d}_{p_{\hat{w}}} \quad (4.408)$$

$$\Leftrightarrow C_{p_{\hat{w}}} \Delta p_{\hat{w}} \geq \bar{d}_{p_{\hat{w}}} - C_{p_{\hat{w}}} p_{\hat{w}} \quad (4.409)$$

$$\Leftrightarrow C_{p_{\hat{w}}} \Delta p_{\hat{w}} \geq d_{p_{\hat{w}}} \quad (4.410)$$

$$\text{return } C_{p_{\hat{w}}}$$

:wrench-control-vector-inequality-constraint-vector *ℰkey (update? t)* [method]

$$\text{return } d_{p_{\hat{w}}} := \bar{d}_{p_{\hat{w}}} - C_{p_{\hat{w}}} p_{\hat{w}}$$

:torque-control-vector-inequality-constraint-matrix [method]

todo

:torque-control-vector-inequality-constraint-vector [method]

todo

:phi-max-vector *ℰkey (update? nil)* [method]

$$\text{return } \phi_{max} \in \mathbb{R}^{N_{invar-joint}}$$

:phi-min-vector $\mathcal{E}key$ (*update? nil*) [method]

return $\phi_{min} \in \mathbb{R}^{N_{invar-joint}}$

:phi-inequality-constraint-matrix $\mathcal{E}key$ (*update? nil*) [method]

$$\phi_{min} \leq \phi + \Delta\phi \leq \phi_{max} \quad (4.411)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \Delta\phi \geq \begin{pmatrix} \phi_{min} - \phi \\ -(\phi_{max} - \phi) \end{pmatrix} \quad (4.412)$$

$$\Leftrightarrow \mathbf{C}_\phi \Delta\phi \geq \mathbf{d}_\phi \quad (4.413)$$

return $\mathbf{C}_\phi := \begin{pmatrix} \mathbf{I} \\ -\mathbf{I} \end{pmatrix} \in \mathbb{R}^{2N_{invar-joint} \times N_{invar-joint}}$

:phi-inequality-constraint-vector $\mathcal{E}key$ (*update? t*) [method]

return $\mathbf{d}_\phi := \begin{pmatrix} \phi_{min} - \phi \\ -(\phi_{max} - \phi) \end{pmatrix} \in \mathbb{R}^{2N_{invar-joint}}$

:config-inequality-constraint-matrix [method]

$$\begin{cases} \mathbf{C}_{p_\theta} \Delta \mathbf{p}_\theta \geq \mathbf{d}_{p_\theta} \\ \mathbf{C}_{p_c} \Delta \mathbf{p}_c \geq \mathbf{d}_{p_c} \\ \mathbf{C}_{p_L} \Delta \mathbf{p}_L \geq \mathbf{d}_{p_L} \\ \mathbf{C}_{p_{\hat{w}}} \Delta \mathbf{p}_{\hat{w}} \geq \mathbf{d}_{p_{\hat{w}}} \\ \mathbf{C}_{p_\tau} \Delta \mathbf{p}_\tau \geq \mathbf{d}_{p_\tau} \\ \mathbf{C}_\phi \Delta \phi \geq \mathbf{d}_\phi \end{cases} \quad (4.414)$$

$$\Leftrightarrow \begin{pmatrix} \mathbf{C}_{p_\theta} & & & & & & \\ & \mathbf{C}_{p_c} & & & & & \\ & & \mathbf{C}_{p_L} & & & & \\ & & & \mathbf{C}_{p_{\hat{w}}} & & & \\ & & & & \mathbf{C}_{p_\tau} & & \\ & & & & & \mathbf{C}_\phi & \end{pmatrix} \begin{pmatrix} \Delta \mathbf{p}_\theta \\ \Delta \mathbf{p}_c \\ \Delta \mathbf{p}_L \\ \Delta \mathbf{p}_{\hat{w}} \\ \Delta \mathbf{p}_\tau \\ \Delta \phi \end{pmatrix} \geq \begin{pmatrix} \mathbf{d}_{p_\theta} \\ \mathbf{d}_{p_c} \\ \mathbf{d}_{p_L} \\ \mathbf{d}_{p_{\hat{w}}} \\ \mathbf{d}_{p_\tau} \\ \mathbf{d}_\phi \end{pmatrix} \quad (4.415)$$

$$\Leftrightarrow \mathbf{C} \Delta \mathbf{q} \geq \mathbf{d} \quad (4.416)$$

return \mathbf{C}

:config-inequality-constraint-vector [method]

return \mathbf{d}

:config-equality-constraint-matrix $\mathcal{E}key$ (*update? nil*) [method]

return $\mathbf{A} \in \mathbb{R}^{0 \times \dim(\mathbf{q})}$ (no equality constraint)

:config-equality-constraint-vector $\mathcal{E}key$ (*update? t*) [method]

return $\mathbf{b} \in \mathbb{R}^0$ (no equality constraint)

:stationery-start-finish-regular-matrix $\mathcal{E}key$ (*update? nil*) [method]

return $\mathbf{W}_{stat} \in \mathbb{R}^{\dim(\mathbf{q}) \times \dim(\mathbf{q})}$

:differential-square-integration-regular-matrix $\mathcal{E}key$ (*diff-order 1*) [method]

return $\mathbf{W}_{sqr,d} \in \mathbb{R}^{\dim(\mathbf{q}) \times \dim(\mathbf{q})}$

:first-differential-square-integration-regular-matrix *ℰkey (update? nil)* [method]
 return $\mathbf{W}_{sqr,1} \in \mathbb{R}^{dim(\mathbf{q}) \times dim(\mathbf{q})}$

:second-differential-square-integration-regular-matrix *ℰkey (update? nil)* [method]
 return $\mathbf{W}_{sqr,2} \in \mathbb{R}^{dim(\mathbf{q}) \times dim(\mathbf{q})}$

:third-differential-square-integration-regular-matrix *ℰkey (update? nil)* [method]
 return $\mathbf{W}_{sqr,3} \in \mathbb{R}^{dim(\mathbf{q}) \times dim(\mathbf{q})}$

:regular-matrix [method]

$$\mathbf{W}_{reg} := \min(k_{max}, \|\mathbf{e}\|^2 + k_{off})\mathbf{I} + k_{stat}\mathbf{W}_{stat} + \sum_{d=1}^3 k_{sqr,d}\mathbf{W}_{sqr,d} \quad (4.417)$$

return $\mathbf{W}_{reg} \in \mathbb{R}^{dim(\mathbf{q}) \times dim(\mathbf{q})}$

:regular-vector [method]

$$\mathbf{v}_{reg} := k_{stat}\mathbf{W}_{stat}\mathbf{q} + \sum_{d=1}^3 k_{sqr,d}\mathbf{W}_{sqr,d}\mathbf{q} \quad (4.418)$$

return $\mathbf{v}_{reg} \in \mathbb{R}^{dim(\mathbf{q})}$

:update-collision-inequality-constraint [method]
 Not implemented yet.

:update-viewer *ℰkey (start-time (send _theta-bst :start-time))* [method]
(finish-time (send _theta-bst :finish-time))
(delta-time (/ (- finish-time start-time) 100.0))
 Update viewer.

:print-setting-information [method]
 Print setting information.

:print-status [method]
 Print status.

:play-animation *ℰkey (robot-env)* [method]
(start-time (send _theta-bst :start-time))
(finish-time (send _theta-bst :finish-time))
(delta-time (/ (- finish-time start-time) 100.0))
(loop? t)
(visualize-callback-func)
 Play motion animation.

:generate-graph *ℰkey (start-time (send _theta-bst :start-time))* [method]
(finish-time (send _theta-bst :finish-time))
(delta-time (/ (- finish-time start-time) 100.0))
(data-dirname /tmp/bspline-dynamic-config-task)
(graph-filename /tmp/bspline-dynamic-config-task/graph.pdf)

Generate graph from configuration and task trajectory.

```
:generate-robot-state-list key (robot-env _robot-env) [method]
  (start-time (send _theta-bst :start-time))
  (finish-time (send _theta-bst :finish-time))
  (joint-name-list (send-all (send robot-env :robot :joint-list) :name))
  (root-link-name (send (car (send robot-env :robot :links)) :name))
  (step-time 0.004)
  (divide-num 100)
  (limb-list (list :rleg :lleg :rarm :larm))
```

Generate and return robot state list.

5 補足

5.1 既存のロボット基礎クラスの拡張

```
joint [class]
  :super propertied-object
  :slots (parent-link)
          (child-link)
          (joint-angle)
          (min-angle)
          (max-angle)
          (default-coords)
          (joint-velocity)
          (joint-acceleration)
          (joint-torque)
          (max-joint-velocity)
          (max-joint-torque)
          (joint-min-max-table)
          (joint-min-max-target)
```

```
:child-link rest args [method]
```

Returns child link of this joint. If any arguments is set, it is passed to the child-link.

Override to support the case that child-link is cascaded-link instantiate. Return the root link of child cascaded-link instantiate in that case.

```
:axis-vector [method]
```

Return joint axis vector. Represented in world coordinates.

return $\mathbf{a}_i \in \mathbb{R}^3$

```
:pos [method]
```

Return joint position. Represented in world coordinates.

```
return  $\boldsymbol{p}_i \in \mathbb{R}^3$ 
```

bodyset-link

[class]

:super	bodyset
:slots	(rot)
	(pos)
	(parent)
	(descendants)
	(worldcoords)
	(manager)
	(changed)
	(geometry::bodies)
	(joint)
	(parent-link)
	(child-links)
	(analysis-level)
	(default-coords)
	(weight)
	(acentroid)
	(inertia-tensor)
	(angular-velocity)
	(angular-acceleration)
	(spacial-velocity)
	(spacial-acceleration)
	(momentum-velocity)
	(angular-momentum-velocity)
	(momentum)
	(angular-momentum)
	(force)
	(moment)
	(ext-force)
	(ext-moment)

:mg

[method]

```
return  $mg = \|\boldsymbol{m}\boldsymbol{g}\|$ 
```

:mg-vec

[method]

```
return  $\boldsymbol{m}\boldsymbol{g}$ 
```

cascaded-link

[class]

:super	cascaded-coords
:slots	(rot)
	(pos)
	(parent)
	(descendants)

```

(worldcoords)
(manager)
(changed)
(links)
(joint-list)
(bodies)
(collision-avoidance-links)
(end-coords-list)

```

:calc-jacobian-from-joint-list *ℰkey* (*union-joint-list*) [method]
(move-target)
(joint-list (mapcar #'(lambda (mt) (send-all (send self :link-list (send mt :parent-link) (transform-coords (mapcar #'(lambda (mt) (make-coords)) move-target)) (translation-axis (mapcar #'(lambda (mt) t) move-target)) (rotation-axis (mapcar #'(lambda (mt) t) move-target))

union-joint-list list of all joints considered in jacobian. column num of jacobian is same with length of union-joint-list.

move-target list of move-target.

joint-list list of joint-list which is contained in each chain of move-target.

transform-coords list of transform-coords of each move-target.

translation-axis list of translation-axis of each move-target.

rotation-axis list of rotation-axis of each move-target.

Get jacobian matrix from following two information: (1) union-joint-list and (2) list of move-target. One recession compared with :calc-jacobian-from-link-list is that child-reverse is not supported. (Only not implemented yet because I do not need such feature in current application.)

:calc-cog-jacobian-from-joint-list *ℰkey* (*union-joint-list*) [method]
(update-mass-properties t)
(translation-axis :z)

union-joint-list list of all joints considered in jacobian. column num of jacobian is same with length of union-joint-list.

Get CoG jacobian matrix from union-joint-list.

:find-link-route *to ℰoptional from* [method]
 Override to support the case that joint does not exist between links. Change from (send to :parent-link) to (send to :parent).

5.2 環境と接触するロボットの関節・リンク構造

2d-planar-contact

[class]

```

:super      cascaded-link
:slots      (_contact-coords  $T_{cnt}$ )
             (_contact-pre-coords  $T_{cnt-pre}$ )

```

二次元平面上の長方形領域での接触座標を表す仮想の関節・リンク構造．

```

:init  $\mathcal{E}key$  (name contact) [method]
          (contact-pre-offset 100)

```

Initialize instance

```

:contact-coords  $\mathcal{E}rest$  args [method]
  return  $T_{cnt} := \{\mathbf{p}_{cnt}, \mathbf{R}_{cnt}\}$ 

```

```

:contact-pre-coords  $\mathcal{E}rest$  args [method]
  return  $T_{cnt-pre} := \{\mathbf{p}_{cnt-pre}, \mathbf{R}_{cnt-pre}\}$ 

```

```

:set-from-face  $\mathcal{E}key$  (face) [method]
          (margin 150.0)

```

set coords and min/max joint angle from face.

look-at-contact [class]

```

:super      cascaded-link
:slots      (_contact-coords  $T_{cnt}$ )

```

ある点を注視するためのカメラ座標を表す仮想の関節・リンク構造．

```

:init  $\mathcal{E}key$  (name look-at) [method]
          (target-pos (float-vector 0 0 0))
          (camera-axis :z)
          (angle-of-view 30.0)

```

Initialize instance

```

:contact-coords  $\mathcal{E}rest$  args [method]
  return  $T_{cnt} := \{\mathbf{p}_{cnt}, \mathbf{R}_{cnt}\}$ 

```

robot-environment [class]

```

:super      cascaded-link
:slots      (_robot  $\mathcal{R}$ )
             (_robot-with-root-virtual  $\hat{\mathcal{R}}$ )
             (_root-virtual-joint-list list of root virtual joint)
             (_contact-list  $\{\mathcal{C}_1, \mathcal{C}_2, \dots, \mathcal{C}_{N_C}\}$ )
             (_variant-joint-list  $\mathcal{J}_{var}$ )
             (_invariant-joint-list  $\mathcal{J}_{invar}$ )
             (_drive-joint-list  $\mathcal{J}_{drive}$ )

```

ロボットとロボット・環境間の接触のクラス .

以下を合わせた関節・リンク構造に関するメソッドが定義されている .

1. 浮遊ルートリンクのための仮想関節付きのロボットの関節
2. 接触位置を定める仮想関節

関節・リンク構造を定めるために , 初期化時に以下を与える

robot \mathcal{R} ロボット (cascaded-link クラスのインスタンス) .

contact-list $\{\mathcal{C}_1, \mathcal{C}_2, \dots, \mathcal{C}_{N_C}\}$ 接触 (2d-planar-contact クラスなどのインスタンス) のリスト .

ロボット R に , 浮遊ルートリンクの変位に対応する仮想関節を付加した仮想関節付きロボット $\hat{\mathcal{R}}$ を内部で保持する .

:init $\mathcal{E}key$ (<i>robot</i>)	[method]
(<i>contact-list</i>)	
(<i>root-virtual-mode :6dof</i>)	
(<i>root-virtual-joint-class-list</i>)	
(<i>root-virtual-joint-axis-list</i>)	
(<i>root-virtual-joint-min-angle-list</i>)	
(<i>root-virtual-joint-max-angle-list</i>)	
Initialize instance	
:dissoc-root-virtual	[method]
dissoc root virtual parent/child structure.	
:init-pose	[method]
set zero joint angle.	
:robot $\mathcal{E}rest$ <i>args</i>	[method]
return \mathcal{R}	
:robot-with-root-virtual $\mathcal{E}rest$ <i>args</i>	[method]
return $\hat{\mathcal{R}}$	
:contact-list $\mathcal{E}rest$ <i>args</i>	[method]
return $\{\mathcal{C}_1, \mathcal{C}_2, \dots, \mathcal{C}_{N_C}\}$	
:contact <i>name</i> $\mathcal{E}rest$ <i>args</i>	[method]
return \mathcal{C}_i	
:variant-joint-list $\mathcal{E}optional$ (<i>jl :nil</i>)	[method]
return \mathcal{J}_{var}	
:invariant-joint-list $\mathcal{E}optional$ (<i>jl :nil</i>)	[method]
return \mathcal{J}_{invar}	
:drive-joint-list $\mathcal{E}optional$ (<i>jl :nil</i>)	[method]
return \mathcal{J}_{drive}	
:root-virtual-joint-list	[method]
return list of root virtual joint	

5.3 irteus の inverse-kinematics 互換関数

cascaded-link

[class]

```

:super    cascaded-coords
:slots    (rot)
           (pos)
           (parent)
           (descendants)
           (worldcoords)
           (manager)
           (changed)
           (links)
           (joint-list)
           (bodies)
           (collision-avoidance-links)
           (end-coords-list)

```

:inverse-kinematics-optmotiongen *target-coords &key (stop 50)*

[method]

```

(link-list)
(move-target)
(debug-view)
(revert-if-fail t)
(transform-coords target-coords)
(translation-axis (cond ((atom move-target) t) (t (make-list
(rotation-axis (cond ((atom move-target) t) (t (make-list
(thre (cond ((atom move-target) 1) (t (make-list (length n
(rthre (cond ((atom move-target) (deg2rad 1)) (t (make-li
(collision-avoidance-link-pair :nil)
(collision-distance-limit 10.0)
(obstacles)
(min-loop)
(root-virtual-mode :fix)
(root-virtual-joint-min-angle-list)
(root-virtual-joint-max-angle-list)
(joint-angle-margin 0.0)
(posture-joint-list)
(posture-joint-angle-list)
(target-posture-scale 0.001)
(norm-regular-scale-max 0.01)
(norm-regular-scale-offset 1.000000e-07)
(pre-process-func)
(post-process-func)
&allow-other-keys

```

Solve inverse kinematics problem with sqp optimization. `;;` target-coords, move-target, rotation-axis, translation-axis `;;` -`z` both list and atom OK. target-coords : The coordinate of the target that returns coordinates. Use a list of targets to solve the IK relative to multiple end links simultaneously. Function is not available to target-coords. link-list : List of links to control. When the target-coords is list, this should be a list of lists. move-target : Specify end-effector coordinate. When the target-coords is list, this should be list too. stop : Maximum number for IK iteration. Default is 50. debug-view : Set `t` to show debug message and visualization. Use `:no-message` to just show the irtvew image. Default is `nil`. revert-if-fail : Set `nil` to keep the angle posture of IK solve iteration. Default is `t`, which return to original position when IK fails. translation-axis : `:x :y :z` for constraint along the x, y, z axis. `:xy :yz :zx` for plane. Default is `t`. rotation-axis : Use `nil` for position only IK. `:x, :y, :z` for the constraint around axis with plus direction. When the target-coords is list, this should be list too. Default is `t`. thre : Threshold for position error to terminate IK iteration. Default is 1 [mm]. rthre : Threshold for rotation error to terminate IK iteration. Default is 0.017453 [rad] (1 deg).

cascaded-link

[`class`]

```

:super      cascaded-coords
:slots      (rot)
             (pos)
             (parent)
             (descendants)
             (worldcoords)
             (manager)
             (changed)
             (links)
             (joint-list)
             (bodies)
             (collision-avoidance-links)
             (end-coords-list)

```



```

(root-virtual-mode :fix)
(root-virtual-joint-invariant? nil)
(root-virtual-joint-min-angle-list)
(root-virtual-joint-max-angle-list)
(joint-angle-margin 0.0)
(posture-joint-list (make-list (length target-coords) 0.0))
(posture-joint-angle-list (make-list (length target-coords) 0.0))
(norm-regular-scale-max 0.001)
(norm-regular-scale-offset 1.000000e-07)
(adjacent-regular-scale 0.0)
(pre-process-func)
(post-process-func)
$allow-other-keys

```

Solve inverse kinematics problem with sqp optimization. `target-coords-list` : The coordinate of the target that returns coordinates. Use a list of targets to solve the IK relative to multiple end links simultaneously. Function is not available to `target-coords`. `move-target-list` : Specify end-effector coordinate. When the `target-coords` is list, this should be list too. `stop` : Maximum number for IK iteration. Default is 50. `debug-view` : Set `t` to show debug message and visualization. Use `:no-message` to just show the irtview image. Default is `nil`. `revert-if-fail` : Set `nil` to keep the angle posture of IK solve iteration. Default is `t`, which return to original position when IK fails. `translation-axis-list` : `:x` `:y` `:z` for constraint along the x, y, z axis. `:xy` `:yz` `:zx` for plane. Default is `t`. `rotation-axis-list` : Use `nil` for position only IK. `:x`, `:y`, `:z` for the constraint around axis with plus direction. When the `target-coords` is list, this should be list too. Default is `t`. `thre` : Threshold for position error to terminate IK iteration. Default is 1 [mm]. `rthre` : Threshold for rotation error to terminate IK iteration. Default is 0.017453 [rad] (1 deg).

robot-model

[class]

```

:super    cascaded-link
:slots    (rot)
           (pos)
           (parent)
           (descendants)
           (worldcoords)
           (manager)
           (changed)
           (links)
           (joint-list)
           (bodies)
           (collision-avoidance-links)
           (end-coords-list)
           (larm-end-coords)
           (rarm-end-coords)
           (lleg-end-coords)
           (rleg-end-coords)
           (head-end-coords)
           (torso-end-coords)

```

```

(larm-root-link)
(rarm-root-link)
(lleg-root-link)
(rleg-root-link)
(head-root-link)
(torso-root-link)
(larm-collision-avoidance-links)
(rarm-collision-avoidance-links)
(larm)
(rarm)
(lleg)
(rleg)
(torso)
(head)
(force-sensors)
(imu-sensors)
(cameras)
(support-polygons)

```

:limb *limb method* *ℰrest args* [method]
 Extend to support to call :inverse-kinematics-optmotiongen.

contact-ik-arg [class]
 :super **cascaded-link**
 :slots (*_contact-coords* *T_{cnt}*)

inverse-kinematics-optmotiongen の *target-coords*, *translation-axis*, *rotation-axis*, *transform-coords* 引数に対応する接触座標を表す仮想の関節・リンク構造 .

:init *ℰkey (target-coords)* [method]
 (*translation-axis*)
 (*rotation-axis*)
 (*transform-coords target-coords*)
 (*name (send target-coords :name)*)
 Initialize instance

:contact-coords *ℰrest args* [method]
 return $T_{cnt} := \{\mathbf{p}_{cnt}, \mathbf{R}_{cnt}\}$

ik-arg-axis->axis-list *ik-arg-axis* [function]
 Convert translation-axis / rotation-axis to axis list.

generate-contact-ik-arg-from-rect-face *ℰkey (rect-face)* [function]
 (*name (send rect-face :name)*)
 (*margin (or (send rect-face :get :margin) 0)*)

Generate contact-ik-arg instance from rectangle face.

```
generate-contact-ik-arg-from-line-segment ℰkey (line-seg) [function]
      (name (send line-seg :name))
      (margin (or (send line-seg :get :margin) 0))
```

Generate contact-ik-arg instance from line segment.

axis->index	<i>axis</i>	[function]
-----------------------	-------------	------------

axis->sgn *axis* [function]

5.4 関節トルク勾配の計算

get-link-jacobian-for-contact-torque	<i>key</i> (robot)	[function]
	(drive-joint-list)	
	(contact-coords)	
	(contact-parent-link)	

contact-coords に対応する接触部位の番号を m とする. *contact-coords* の位置を $p_m \in \mathbb{R}^3$, *drive-joint-list* の関節角度ベクトルを $\psi \in \mathbb{R}^{(N_{\text{drive-joint}})}$ として, 次式を満たすヤコビ行列 J_m を返す.

$$\mathbf{J}_m = \begin{pmatrix} \mathbf{j}_m^{(1)} & \mathbf{j}_m^{(2)} & \cdots & \mathbf{j}_m^{N_{drive-joint}} \end{pmatrix} \quad (5.1)$$

$$\mathbf{j}_m^{(i)} = \begin{cases} \bar{\mathbf{j}}_m^{(i)} & \text{接触リンクが } i \text{ 番目の駆動関節変位に依存している場合} \\ \mathbf{0} & \text{otherwise} \end{cases} \quad (5.2)$$

$\bar{j}_m^{(i)}$ は基礎ヤコビ行列の列ベクトルで次式で表される.

ψ_i が回転関節の場合

$$\bar{\mathbf{j}}_m^{(i)} = \begin{pmatrix} \mathbf{a}_{\psi_i} \times (\mathbf{p}_m - \mathbf{p}_{\psi_i}) \\ \mathbf{a}_{\psi_i} \end{pmatrix} \quad (5.3)$$

ψ_i が直動関節の場合

$$\bar{\mathbf{j}}_m^{(i)} = \begin{pmatrix} \mathbf{a}_{\psi_i} \\ \mathbf{0} \end{pmatrix} \quad (5.4)$$

$\mathbf{a}_{\psi_i}, \mathbf{p}_{\psi_i} \in \mathbb{R}^3$ は i 番目の関節の回転軸ベクトルと位置である。

return $\mathbf{J}_m \in \mathbb{R}^{6 \times N_{drive-joint}}$

get-contact-torque	<i>key</i> (robot)	[function]
	(drive-joint-list)	
	(wrench-list)	
	(contact-target-coords-list)	
	(contact-attention-coords-list)	

ロボットの接触部位に加わる接触レンチによって生じる関節トルク τ^{cnt} は、以下で得られる。

$$\boldsymbol{\tau}^{cnt} = \sum_{m=1}^{N_{cnt}} \mathbf{J}_m^T \mathbf{w}_m \quad (5.5)$$

w_m は m 番目の接触部位で受ける接触レンチである.

```

return  $\tau^{cnt} \in \mathbb{R}^{N_{drive-joint}}$ 

```

get-contact-torque-jacobian *key (robot)* [function]
(joint-list)
(drive-joint-list)
(wrench-list)
(contact-target-coords-list)
(contact-attention-coords-list)

以下では, p_B^A は A から B へ向かう位置ベクトルをワールド座標系で表記したものとす. A, B は, $drive-joint-list$ の関節位置 ψ_i , $joint-list$ の関節位置 θ_i , $contact-coords$ の位置 m のいずれかを指す.

$$\frac{\partial \tau^{cnt}}{\partial \theta} = \frac{\partial}{\partial \theta} \sum_{m=1}^{N_{cnt}} \mathbf{J}_m^T \mathbf{w}_m \quad (5.6)$$

$$= \frac{\partial}{\partial \theta} \sum_{m=1}^{N_{cnt}} \left(\mathbf{j}_m^{(1)} \quad \mathbf{j}_m^{(2)} \quad \dots \quad \mathbf{j}_m^{(N_{drive-joint})} \right)^T \mathbf{w}_m \quad (5.7)$$

$$= \sum_{m=1}^{N_{cnt}} \frac{\partial}{\partial \theta} \begin{pmatrix} \mathbf{w}_m^T \mathbf{j}_m^{(1)} \\ \mathbf{w}_m^T \mathbf{j}_m^{(2)} \\ \vdots \\ \mathbf{w}_m^T \mathbf{j}_m^{(N_{drive-joint})} \end{pmatrix} \quad (5.8)$$

$$= \sum_{m=1}^{N_{cnt}} \left[\mathbf{w}_m^T \frac{\partial}{\partial \theta_j} \mathbf{j}_m^{(i)} \right]_{i,j} \quad (i = 1, 2, \dots, N_{drive-joint}, \quad j = 1, 2, \dots, N_{joint}) \quad (5.9)$$

したがって, 各接触力によるトルクのヤコビ行列の各要素は次式で得られる.

ψ_i が回転関節の場合

$$\mathbf{w}_m^T \frac{\partial}{\partial \theta_j} \mathbf{j}_m^{(i)} = \begin{pmatrix} \mathbf{f}_m \\ \mathbf{n}_m \end{pmatrix}^T \frac{\partial}{\partial \theta_j} \begin{pmatrix} \mathbf{a}_{\psi_i} \times \mathbf{p}_m^{\psi_i} \\ \mathbf{a}_{\psi_i} \end{pmatrix} \quad (5.10)$$

$$= \mathbf{f}_m^T \frac{\partial}{\partial \theta_j} (\mathbf{a}_{\psi_i} \times \mathbf{p}_m^{\psi_i}) + \mathbf{n}_m^T \frac{\partial}{\partial \theta_j} \mathbf{a}_{\psi_i} \quad (5.11)$$

$$= \mathbf{f}_m^T \left\{ \left(\frac{\partial}{\partial \theta_j} \mathbf{a}_{\psi_i} \right) \times \mathbf{p}_m^{\psi_i} + \mathbf{a}_{\psi_i} \times \left(\frac{\partial}{\partial \theta_j} \mathbf{p}_m - \frac{\partial}{\partial \theta_j} \mathbf{p}_{\psi_i} \right) \right\} + \mathbf{n}_m^T \frac{\partial}{\partial \theta_j} \mathbf{a}_{\psi_i} \quad (5.12)$$

ψ_i が直動関節の場合

$$\mathbf{w}_m^T \frac{\partial}{\partial \theta_j} \mathbf{j}_m^{(i)} = \begin{pmatrix} \mathbf{f}_m \\ \mathbf{n}_m \end{pmatrix}^T \frac{\partial}{\partial \theta_j} \begin{pmatrix} \mathbf{a}_{\psi_i} \\ \mathbf{0} \end{pmatrix} \quad (5.13)$$

$$= \mathbf{f}_m^T \frac{\partial}{\partial \theta_j} \mathbf{a}_{\psi_i} \quad (5.14)$$

$\frac{\partial}{\partial \theta_j} \mathbf{a}_{\psi_i}$ (*drive-jnt-axis-derivative*), $\frac{\partial}{\partial \theta_j} \mathbf{p}_{\psi_i}$ (*drive-jnt-pos-derivative*) は以下のように計算される.

(A) 関節 θ_j が関節 ψ_i よりもルートリンクに近いとき, もしくは関節 θ_j と関節 ψ_i が同一のとき,

(I) 関節 θ_j が回転関節のとき, 回転系での基礎方程式から,

$$\frac{\partial}{\partial \theta_j} \mathbf{a}_{\psi_i} = \mathbf{a}_{\theta_j} \times \mathbf{a}_{\psi_i} \quad (5.15)$$

$$\frac{\partial}{\partial \theta_j} \mathbf{p}_{\psi_i} = \mathbf{a}_{\theta_j} \times \mathbf{p}_{\psi_i}^{\theta_j} \quad (5.16)$$

(II) 関節 θ_j が直動関節のとき

$$\frac{\partial}{\partial \theta_j} \mathbf{a}_{\psi_i} = \mathbf{0} \quad (5.17)$$

$$\frac{\partial}{\partial \theta_j} \mathbf{p}_{\psi_i} = \mathbf{a}_{\theta_j} \quad (5.18)$$

(B) (A) でないとき，つまり

関節 ψ_i が関節 θ_j よりもルートリンクに近いとき，もしくは，ルートリンクから関節 θ_j までの間とルートリンクから関節 ψ_i までの間に共通の関節が存在しないとき，関節 θ_j の変化は関節 ψ_i の位置，回転軸のベクトルに影響を与えないため，

$$\frac{\partial}{\partial \theta_j} \mathbf{a}_{\psi_i} = \mathbf{0} \quad (5.19)$$

$$\frac{\partial}{\partial \theta_j} \mathbf{p}_{\psi_i} = \mathbf{0} \quad (5.20)$$

$\frac{\partial}{\partial \theta_j} \mathbf{p}_m$ (*contact-pos-derivative*) は以下のように計算される．

(a) 関節 θ_j の変位が \mathbf{p}_m に影響を与えるとき (このパターンは *contact-target-coords* が仮想関節の先が設置されている場合などに発生する)

(i) 関節 θ_j が回転関節のとき

$$\frac{\partial}{\partial \theta_j} \mathbf{p}_m = \mathbf{a}_{\theta_j} \times \mathbf{p}_m^{\theta_j} \quad (5.21)$$

(ii) 関節 θ_j が直動関節のとき

$$\frac{\partial}{\partial \theta_j} \mathbf{p}_m = \mathbf{a}_{\theta_j} \quad (5.22)$$

(b) (a) でないとき，つまり

関節 θ_j の変位が \mathbf{p}_m に影響を与えないとき

$$\frac{\partial}{\partial \theta_j} \mathbf{p}_m = \mathbf{0} \quad (5.23)$$

get-link-jacobian-for-gravity-torque *key* (*robot*) [function]
(drive-joint-list)
(gravity-link)

gravity-link のリンク番号を k とする．*gravity-link* の重心位置を $\mathbf{p}_{cog,k} \in \mathbb{R}^3$ ，*drive-joint-list* の関節角度ベクトルを $\psi \in \mathbb{R}^{N_{drive-joint}}$ として，次式を満たすヤコビ行列 $\mathbf{J}_{cog,k}$ を返す．

$$\dot{\mathbf{p}}_{cog,k} = \mathbf{J}_{cog,k} \dot{\psi} \quad (5.24)$$

$$= \sum_{i=1}^{N_k} \mathbf{j}_{cog,k}^{(i)} \dot{\psi}_i \quad (5.25)$$

$$\mathbf{j}_{cog,k}^{(i)} = \begin{cases} \mathbf{a}_{\psi_i} \times (\mathbf{p}_{cog,k} - \mathbf{p}_{\psi_i}) & (1 \leq i \leq N_k) \\ \mathbf{0}_3 & (N_k + 1 \leq i \leq N_{drive-joint}) \end{cases} \quad (5.26)$$

$\mathbf{a}_{\psi_i}, \mathbf{p}_{\psi_i} \in \mathbb{R}^3$ は i 番目の関節の回転軸ベクトルと位置である．*gravity-link* よりもルート側にある関節の番号を $1, \dots, N_k$ ，*gravity-link* よりも末端側にある関節の番号を $N_k + 1, \dots, N_{drive-joint}$ とする．リンクの重心位置と関節角度の依存関係から，ヤコビ行列の右には次式のように零ベクトルが並ぶ．

$$\mathbf{J}_{cog,k} = \begin{pmatrix} \mathbf{j}_{cog,k}^{(1)} & \cdots & \mathbf{j}_{cog,k}^{(N_k)} & \mathbf{j}_{cog,k}^{(N_k+1)} & \cdots & \mathbf{j}_{cog,k}^{(N_{drive-joint})} \end{pmatrix} \quad (5.27)$$

$$= \begin{pmatrix} \mathbf{j}_{cog,k}^{(1)} & \cdots & \mathbf{j}_{cog,k}^{(N_k)} & \mathbf{0} & \cdots & \mathbf{0} \end{pmatrix} \quad (5.28)$$

return $\mathbf{J}_{cog,k} \in \mathbb{R}^{3 \times N_{drive-joint}}$

get-gravity-torque $\mathcal{E}key$ (robot) [function]
 (drive-joint-list)
 (gravity-link-list)

ロボットのリンク自重によって生じる関節トルク τ^{grav} は、ロボットモーション P111 式 (3.3.22) より以下で得られる。

$$\tau^{grav} = \left(\sum_{k=1}^{N_{gravity-link}} m_k \mathbf{J}_{cog,k}^T \right) \mathbf{g} \quad (5.29)$$

m_k は k 番目のリンクの質量である。

return $\tau^{grav} \in \mathbb{R}^{N_{drive-joint}}$

get-gravity-torque-jacobian $\mathcal{E}key$ (robot) [function]
 (joint-list)
 (drive-joint-list)
 (gravity-link-list)

式 (5.28) の $\mathbf{J}_{cog,k}$ を以下のように分解して利用する。

$$\mathbf{J}_{cog,k} = \begin{pmatrix} \dot{\mathbf{j}}_{cog,x,k}^T \\ \dot{\mathbf{j}}_{cog,y,k}^T \\ \dot{\mathbf{j}}_{cog,z,k}^T \end{pmatrix} = \begin{pmatrix} \left(\frac{\partial p_{cog,x,k}}{\partial \psi} \right)^T \\ \left(\frac{\partial p_{cog,y,k}}{\partial \psi} \right)^T \\ \left(\frac{\partial p_{cog,z,k}}{\partial \psi} \right)^T \end{pmatrix} \quad (5.30)$$

これを式 (5.29) に代入すると、

$$\tau^{grav} = \left(\sum_{k=1}^{N_{gravity-link}} m_k \mathbf{J}_{cog,k}^T \right) \mathbf{g} \quad (5.31)$$

$$= \sum_{k=1}^{N_{gravity-link}} m_k \begin{pmatrix} \dot{\mathbf{j}}_{cog,x,k} & \dot{\mathbf{j}}_{cog,y,k} & \dot{\mathbf{j}}_{cog,z,k} \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} \quad (5.32)$$

$$= \sum_{k=1}^{N_{gravity-link}} m_k g \dot{\mathbf{j}}_{cog,z,k} \quad (5.33)$$

$$= \sum_{k=1}^{N_{gravity-link}} m_k g \frac{\partial p_{cog,z,k}}{\partial \psi} \quad (5.34)$$

$joint-list$ の関節角度ベクトルを $\theta \in \mathbb{R}^{N_{joint}}$ 、 $drive-joint-list$ の関節角度ベクトルを $\psi \in \mathbb{R}^{N_{drive-joint}}$ とする。トルク勾配行列 $\frac{\partial \tau^{grav}}{\partial \theta}$ は次式で得られる。これは対称行列である。

$$\frac{\partial \tau^{grav}}{\partial \theta} = \sum_{k=1}^{N_{gravity-link}} m_k g \frac{\partial^2 p_{cog,z,k}}{\partial \psi \partial \theta} \quad (5.35)$$

$$\frac{\partial^2 p_{cog,z,k}}{\partial \psi \partial \theta} = \left[\frac{\partial^2 p_{cog,z,k}}{\partial \psi_i \partial \theta_j} \right]_{i=1, \dots, N_{drive-joint}, j=1, \dots, N_{joint}} \quad (5.36)$$

つまり

$$\frac{\partial \tau^{grav}}{\partial \theta} = \left[\sum_{k=1}^{N_{gravity-link}} m_k g \frac{\partial^2 p_{cog,z,k}}{\partial \psi_i \partial \theta_j} \right]_{i=1, \dots, N_{drive-joint}, j=1, \dots, N_{joint}} \quad (5.37)$$

return $\frac{\partial \tau^{grav}}{\partial \theta} \in \mathbb{R}^{N_{drive-joint} \times N_{joint}}$