Manipulation motion planning

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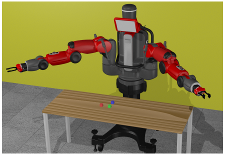
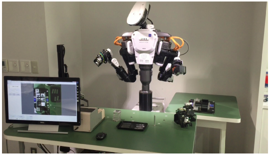
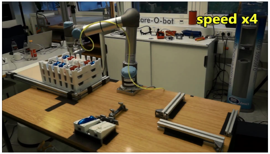
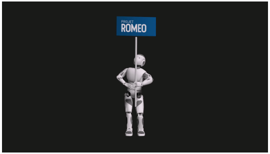
A few examples









Definitions

A manipulation motion

- is the motion of
  - one or several robots and of
  - one or several objects
- such that each object
  - either is in a stable position, or
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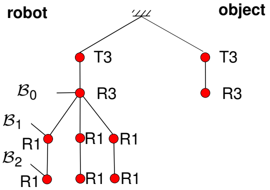
Composite robot

Kinematic chain composed of each robot and of each object



$$\mathbf{q} = (q_0, \cdots, q_{n_r}, q_{n_r+1}, \cdots, q_{n_r+n_o})$$

The configuration space of a composite robot is the cartesian product of the configuration spaces of each robot and object.

$$\mathcal{C} = \mathcal{C}_{r1} \times \mathcal{C}_{r_{nb\ robots}} \times SE(3)^{nb\ objets}$$

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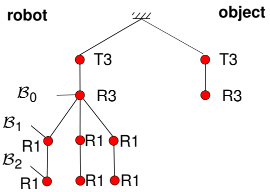

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Numerical constraints

Constraints to which manipulation motions are subject can be expressed numerically.

- Numerical constraints:

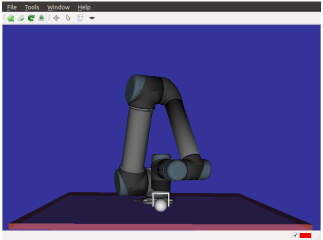
$$f(\mathbf{q}) = 0, \quad \begin{array}{l} m \in \mathbb{N}, \\ f \in C^1(\mathcal{C}, \mathbb{R}^m) \end{array}$$

  - `setConstantRightHandSide(True)`
- Parameterizable numerical constraints:

$$f(\mathbf{q}) = f_0, \quad \begin{array}{l} m \in \mathbb{N}, \\ f \in C^1(\mathcal{C}, \mathbb{R}^m) \\ f_0 \in \mathbb{R}^m \end{array}$$

  - `setConstantRightHandSide(False)`

Example: robot manipulating a ball



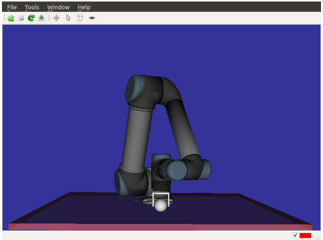
$$\mathcal{C} = [-\pi, \pi]^6 \times \mathbb{R}^3 \quad (1)$$

$$\mathbf{q} = (q_0, \cdots, q_5, x_b, y_b, z_b) \quad (2)$$

Two *states*:

- `placement`: the ball is lying on the table,
- `grasp`: the ball is hold by the end-effector.

Example: robot manipulating a ball



Each state is defined by a numerical constraint

- placement

$$z_b = 0$$

- grasp

$$\mathbf{x}_{gripper}(q_0, \cdots, q_5) - \begin{pmatrix} x_b \\ y_b \\ z_b \end{pmatrix} = 0$$

Each state is a sub-manifold of the configuration space

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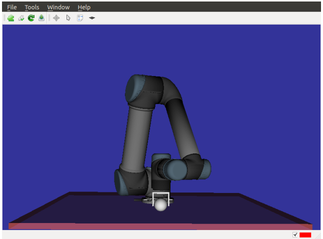

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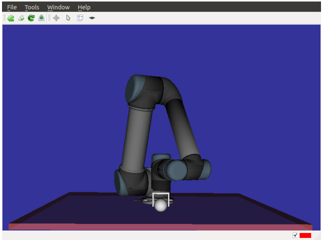
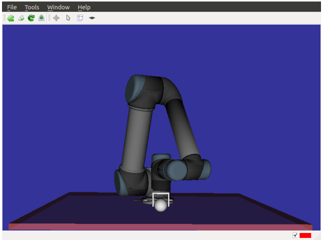


Two *types of motion*:

- `transit`: the ball is lying and **fixed** on the table,
- `transfer`: the ball moves with the end-effector.

Example: robot manipulating a ball

Motion constraints



- `transit`

$$\left.\begin{array}{rcl} x_b & = & x_0 \\ y_b & = & y_0 \end{array}\right\} \text{ parameterizable}$$

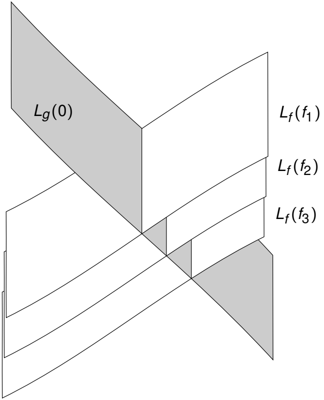
$$\left. z_b = 0 \right\} \text{ simple}$$

- `transfer`

$$\mathbf{x}_{gripper}(q_0, \cdots, q_5) - \begin{pmatrix} x_b \\ y_b \\ z_b \end{pmatrix} = 0$$

Foliation

Motion constraints define a foliation of the admissible configuration space (`grasp` $\cup$ `placement`).



- f: position of the ball

$$L_f(f_1) = \{\mathbf{q} \in \mathcal{C}, f(\mathbf{q}) = f_1\}$$

- g: grasp of the ball

$$L_g(0) = \{\mathbf{q} \in \mathcal{C}, g(\mathbf{q}) = 0\}$$

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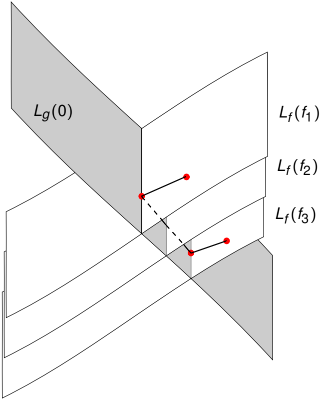

Solution to a manipulation planning problem is a concatenation of *transit* and *transfer* paths.

General case

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- trajectories of the system are subject to
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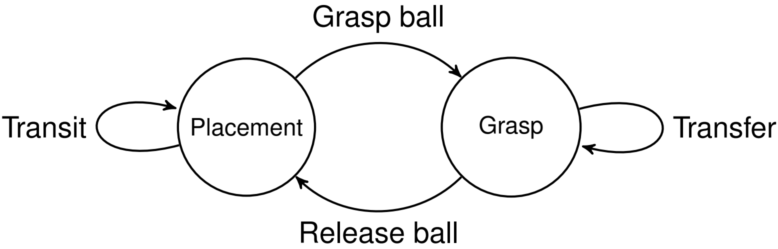
Constraint graph

A manipulation planning problem can be represented by a *manipulation graph*.

- **Nodes** or *states* are numerical constraints.
- **Edges** or *transitions* are parameterizable numerical constraints.



Projecting configuration on constraint

Newton-Raphson algorithm

- $\mathbf{q}_0$ configuration,
- $f(\mathbf{q}) = 0$ non-linear constraint,
- ϵ numerical tolerance

Projection $(\mathbf{q}_0, f)$:

$\mathbf{q} = \mathbf{q}_0$; $\alpha = 0.95$

for i from 1 to max_iter:

$$\mathbf{q} = \mathbf{q} - \alpha \left(\frac{\partial f}{\partial \mathbf{q}}(\mathbf{q})\right)^{+} f(\mathbf{q})$$

if $\|f(\mathbf{q})\| < \epsilon$: return $\mathbf{q}$

return failure

Steering method

Mapping $\mathcal{SM}$ from $\mathcal{C} \times \mathcal{C}$ to $C^1([0,1], \mathcal{C})$ such that

$$\mathcal{SM}(\mathbf{q}_0, \mathbf{q}_1)(0) = \mathbf{q}_0$$
$$\mathcal{SM}(\mathbf{q}_0, \mathbf{q}_1)(1) = \mathbf{q}_1$$

Constrained steering method

Let

- $\mathcal{SM}$ be a steering method
- $f \in C^1(\mathcal{C}, \mathbb{R}^m)$ be a numerical constraint.

A constrained steering method $\mathcal{S}\bar{\mathcal{M}}$ of constraint f is a steering method such that

$$\forall t \in [0, 1], f(\mathcal{S}\bar{\mathcal{M}}(t)) = 0$$

It can be defined by projection

$$\mathcal{S}\bar{\mathcal{M}} = proj \circ \mathcal{SM}$$

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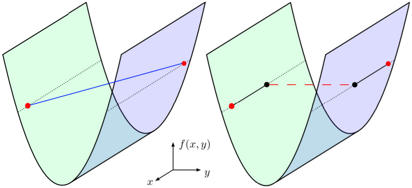
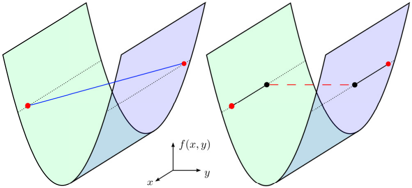
Projecting path on constraint

- *path*: mapping from $[0, 1]$ to $\mathcal{C}$
- $f(\mathbf{q}) = 0$ non-linear constraint,

Applying Newton Raphson at each point may result in a discontinuous path



Discontinuous Projection



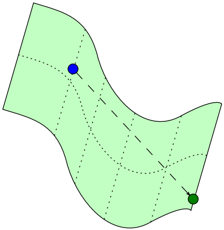
$$\mathcal{C} = \mathbb{R}^2, f(x, y) = y^2 - 1$$

$$\frac{\partial f}{\partial \mathbf{q}} = \begin{pmatrix} 0 & 2y \end{pmatrix}, \; \frac{\partial f}{\partial \mathbf{q}}^+ = \begin{pmatrix} 0 \\ \frac{1}{2y} \end{pmatrix} \text{ ou } \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$y_{i+1} = y_i + \frac{1 - y_i^2}{2y_i}$$

Testing projection continuity

- The initial path is sampled and successive samples are projected,
-
-



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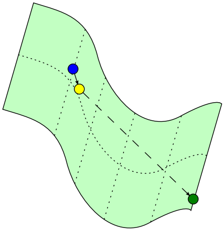

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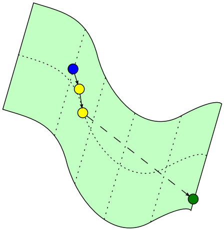

Testing projection continuity

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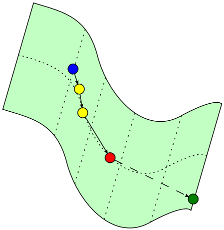
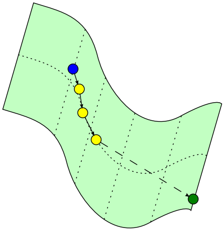
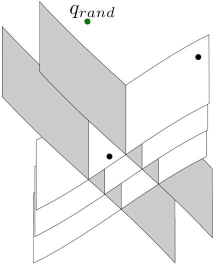


Testing projection continuity

- The initial path is sampled and successive samples are projected,
- if 2 successive projections are too far away, an intermediate sample is selected.
- Choosing appropriate sampling ensures us continuity of the projection.



Algorithm
Manipulation RRT



Manipulation RRT

$\mathbf{q}_{rand}$ = shoot_random_config()

for each connected component:

- $\mathbf{q}_{near}$ = nearest_neighbor($\mathbf{q}_{rand}$, *roadmap*)
- T = select_transition($\mathbf{q}_{near}$)
- $\mathbf{q}_{proj}$ = generate_target_config($\mathbf{q}_{near}$, $\mathbf{q}_{rand}$, T)
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for $\mathbf{q} \in (\mathbf{q}^1_{new}, \dots, \mathbf{q}^{n_{cc}}_{new})$:

- connect ($\mathbf{q}$, roadmap)

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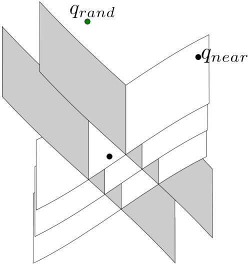

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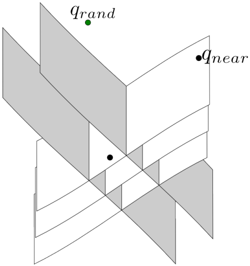

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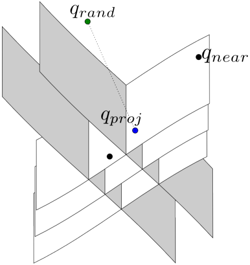

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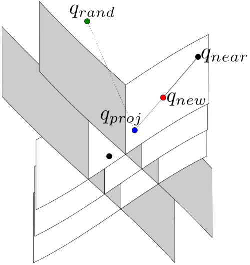

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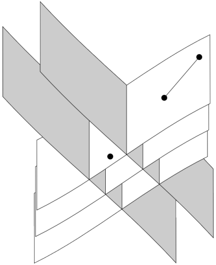

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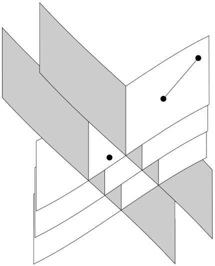

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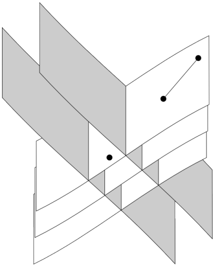

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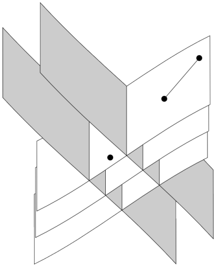

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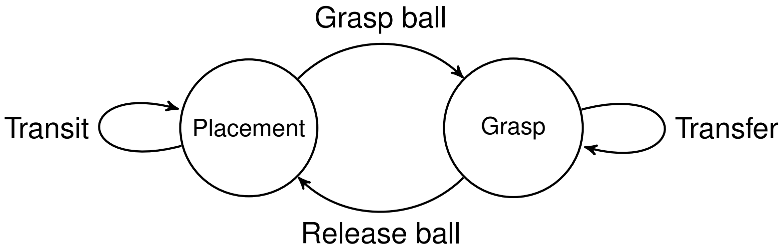
Select transition

T = select_transition($\mathbf{q}_{near}$)

Outward transitions of each state are given a probability distribution. The transition from a state to another state is chosen by random sampling.



Generate target configuration

$\mathbf{q}_{proj}$ = generate_target_config($\mathbf{q}_{near}, \mathbf{q}_{rand}, T$)

Once transition T has been selected, $\mathbf{q}_{rand}$ is *projected* onto the destination state S_{dest} in a configuration reachable by $\mathbf{q}_{near}$.

$$f_T(\mathbf{q}_{proj}) = f_T(\mathbf{q}_{near})$$
$$f_{S_{dest}}(\mathbf{q}_{proj}) = 0$$

Extend

$\mathbf{q}_{new} = \text{extend}(\mathbf{q}_{near}, \mathbf{q}_{proj}, T)$

Project straight path $[\mathbf{q}_{near}, \mathbf{q}_{proj}]$ on transition constraint:

- if projection successful and projected path collision free

$$\mathbf{q}_{new} \leftarrow \mathbf{q}_{proj}$$

- otherwise $(\mathbf{q}_{near}, \mathbf{q}_{new}) \leftarrow$ largest path interval tested as collision-free with successful projection.

$$\forall \mathbf{q} \in (\mathbf{q}_{near}, \mathbf{q}_{new}),\ f_T(\mathbf{q}) = f_T(\mathbf{q}_{near})$$

Extend

$\mathbf{q}_{new} = \text{extend}(\mathbf{q}_{near}, \mathbf{q}_{proj}, T)$

Project straight path $[\mathbf{q}_{near}, \mathbf{q}_{proj}]$ on transition constraint:

- if projection successful and projected path collision free

$$\mathbf{q}_{new} \leftarrow \mathbf{q}_{proj}$$

- otherwise $(\mathbf{q}_{near}, \mathbf{q}_{new}) \leftarrow$ largest path interval tested as collision-free with successful projection.

$$\forall \mathbf{q} \in (\mathbf{q}_{near}, \mathbf{q}_{new}), \; f_T(\mathbf{q}) = f_T(\mathbf{q}_{near})$$

Extend

$\mathbf{q}_{new}$ = extend($\mathbf{q}_{near}$, $\mathbf{q}_{proj}$, T)

Project straight path $[\mathbf{q}_{near}, \mathbf{q}_{proj}]$ on transition constraint:

- if projection successful and projected path collision free

$$\mathbf{q}_{new} \leftarrow \mathbf{q}_{proj}$$

- otherwise $(\mathbf{q}_{near}, \mathbf{q}_{new}) \leftarrow$ largest path interval tested as collision-free with successful projection.

$$\forall \mathbf{q} \in (\mathbf{q}_{near}, \mathbf{q}_{new}),\ f_T(\mathbf{q}) = f_T(\mathbf{q}_{near})$$

Connect

connect ($\mathbf{q}$, roadmap)

for each connected component *cc* not containing $\mathbf{q}$:

for all *n* closest config $\mathbf{q}_1$ to $\mathbf{q}$ in *cc*:

- connect ($\mathbf{q}$, $\mathbf{q}_1$)

Connect

connect ($\mathbf{q}_0$, $\mathbf{q}_1$):

S_0 = state ($\mathbf{q}_0$)

S_1 = state ($\mathbf{q}_1$)

T = transition (S_0, S_1)

if T and $f_T(\mathbf{q}_0) == f_T(\mathbf{q}_1)$:

if p = projected_path (T, $\mathbf{q}_0$, $\mathbf{q}_1$) collision-free:

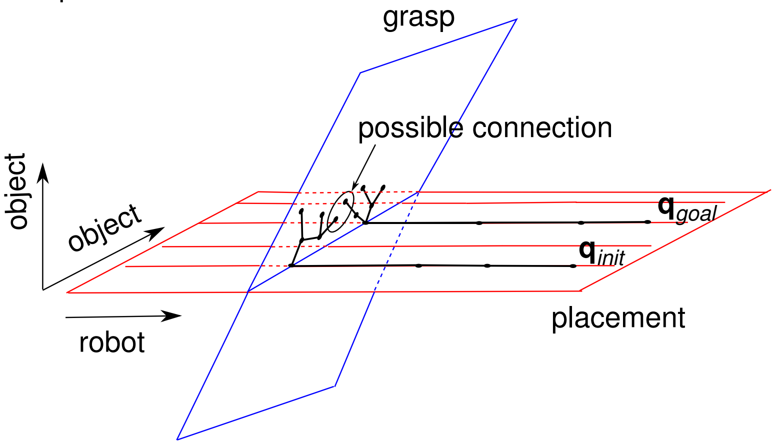
roadmap.insert_edge (T, $\mathbf{q}_0$,$\mathbf{q}_1$)

return

Connecting trees

Manipulation RRT is initialized with $\mathbf{q}_{init}$, $\mathbf{q}_{goal}$.

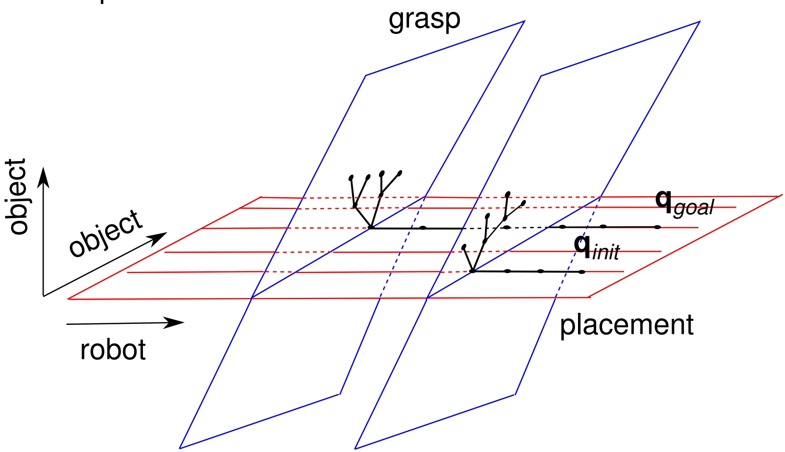
- 2 connected components.
- possible connection.



Connecting trees: general case

Manipulation RRT is initialized with $\mathbf{q}_{init}$, $\mathbf{q}_{goal}$.

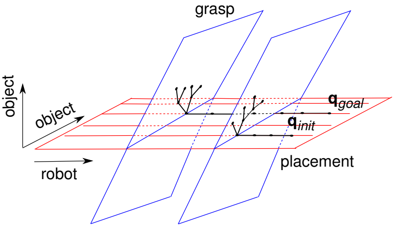
- 2 connected components,
- no possible connection.

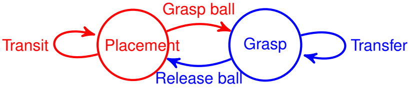


Connecting trees: general case

Manipulation RRT is initialized with $\mathbf{q}_{init}, \mathbf{q}_{goal}$.

- 2 connected components,
- no possible connection.





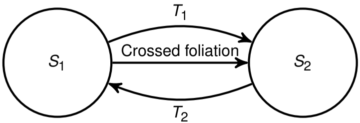
Crossed foliation transition: generate target configuration

$\mathbf{q}_{proj}$ =
generate_target_config($\mathbf{q}_{near}, \mathbf{q}_{rand}, T$)

$\mathbf{q}_1 \leftarrow$ pick configuration

- in state S_1,
- not in same connected component as $\mathbf{q}_{near}$

$$f_{T_1}(\mathbf{q}_{proj}) = f_{T_1}(\mathbf{q}_{near})$$
$$f_{T_2}(\mathbf{q}_{proj}) = f_{T_2}(\mathbf{q}_1)$$
$$f_{S_2}(\mathbf{q}_{proj}) = 0$$



Crossed foliation transition: extend

$\mathbf{q}_{new}$ = extend($\mathbf{q}_{near}$, $\mathbf{q}_{proj}$, T_1)

Project straight path $[\mathbf{q}_{near}, \mathbf{q}_{proj}]$ on T_1 constraint:

- if projection successful and projected path collision free

$$\mathbf{q}_2 \leftarrow \mathbf{q}_{proj}$$

$$f_{T_2}(\mathbf{q}_2) = f_{T_2}(\mathbf{q}_1)$$
$$f_{S_2}(\mathbf{q}_2) = 0$$

- $\mathbf{q}_2$ is connectable to $\mathbf{q}_1$ via T_2.

Crossed foliation transition: extend

$\mathbf{q}_{new} = \text{extend}(\mathbf{q}_{near}, \mathbf{q}_{proj}, T_1)$

Project straight path $[\mathbf{q}_{near}, \mathbf{q}_{proj}]$ on T_1 constraint:

- if projection successful and projected path collision free

$$\mathbf{q}_2 \leftarrow \mathbf{q}_{proj}$$

$$\begin{aligned} f_{T_2}(\mathbf{q}_2) &= f_{T_2}(\mathbf{q}_1) \\ f_{S_2}(\mathbf{q}_2) &= 0 \end{aligned}$$

- $\mathbf{q}_2$ is connectable to $\mathbf{q}_1$ via T_2.

Relative positions as numerical constraints

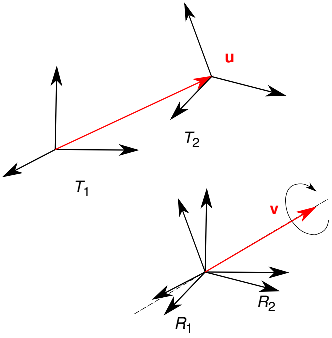
- $T_1 = T_{(R_1,t_1)} \in SE(3)$,
  $T_2 = T_{(R_2,t_2)} \in SE(3)$.
- $T_{2/1} = T_1^{-1} \circ T_2$ can be represented by a vector of dimension 6:

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{v} \end{pmatrix}$$

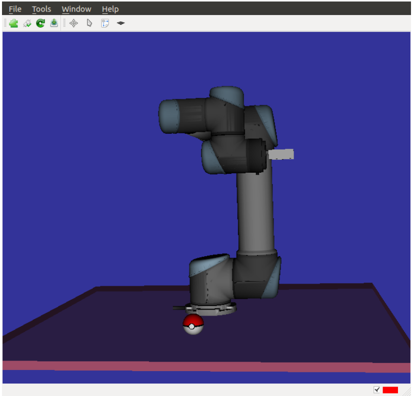
where

$$\mathbf{u} = R_1^T(t_2 - t_1)$$

$R_1^T R_2$ matrix of the rotation around axis $\mathbf{v}/\|\mathbf{v}\|$ and of angles $\|\mathbf{v}\|$.



A few words about the BE



- `script/grasp_ball.py`