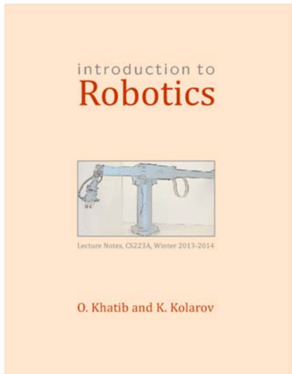


Movie Segment

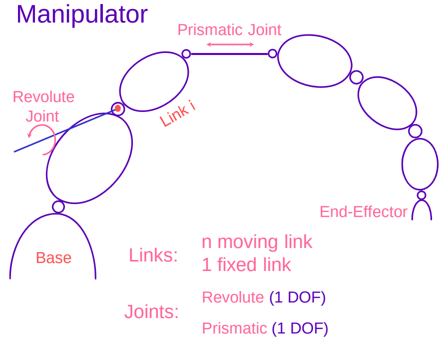
Pet-Proto Robot Navigates Obstacles, Boston Dynamics, 2012

Kinematics

Spatial Descriptions

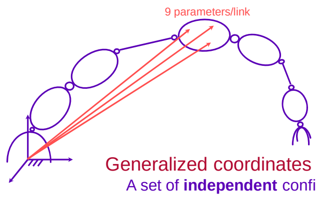
- Task Description
- Transformations
- Representations

Manipulator



Configuration Parameters

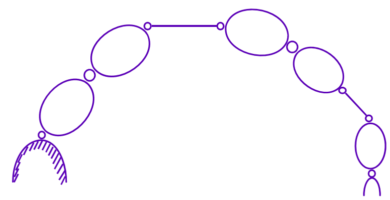
A set of position parameters that describes the full configuration of the system.



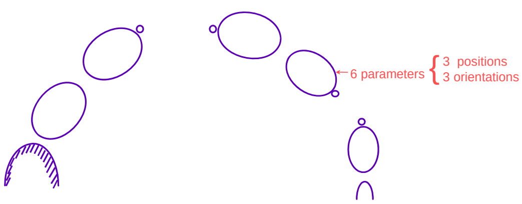
Generalized coordinates
A set of **independent** configuration parameters

Degrees of Freedom
Number of generalized coordinates

Generalized Coordinates

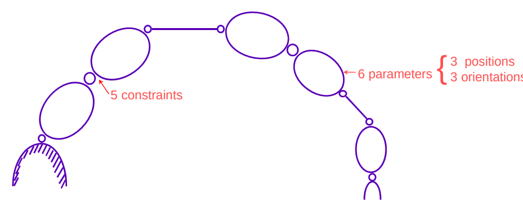


Generalized Coordinates



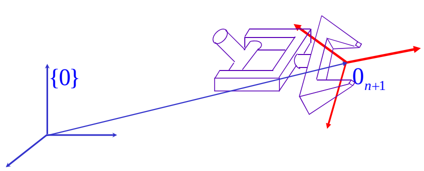
n moving links: 6n parameters

Generalized Coordinates



n moving links: 6n parameters
n 1 d.o.f. joints: 5n constraints
d.o.f. (system): 6n - 5n = n

End-Efector Configuration Parameters



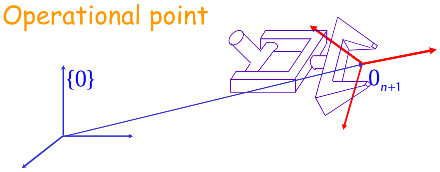
A set of m parameters:

$(x_1, x_2, x_3, \dots, x_m)$

that completely specifies the end-effector position and orientation with respect to $\{0\}$

Operational Coordinates

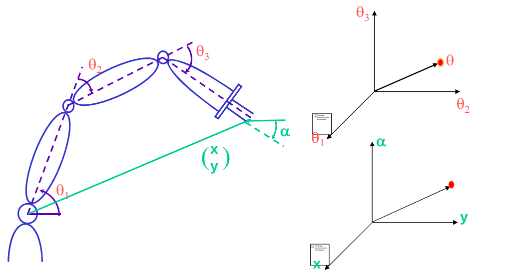
O_{n+1} : Operational point



A set $x_1, x_2, \dots, x_{m_0}$
of m_0 independent configuration parameters

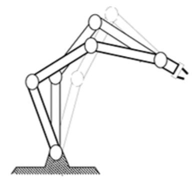
m_0 : number of degrees of freedom of the end-effector.

Joint Coordinates → Joint Space



Operational Coordinates → Operational Space

Redundancy

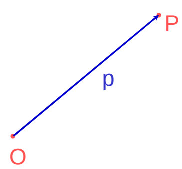


A robot is said to be redundant if

$n > m_0$

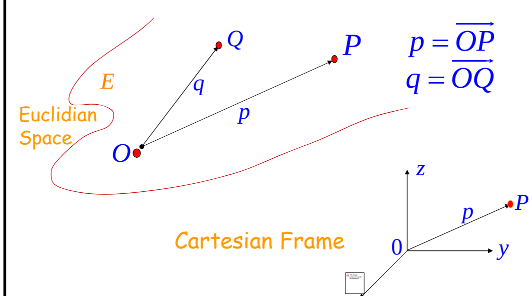
Degrees of redundancy: $n - m_0$

Position of a Point



With respect to a fixed origin O, the position of a point P is described by the vector OP or simply by p.

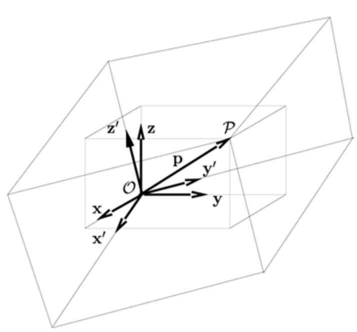
Rigid Body Configuration



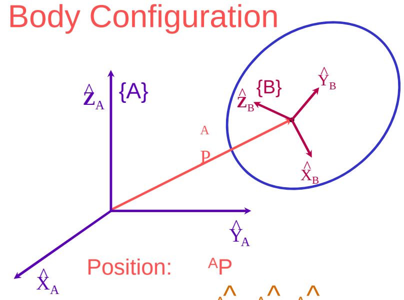
$p = \overrightarrow{OP}$

$q = \overrightarrow{OQ}$

Coordinate Frames



Rigid Body Configuration



Position: ^{A}P

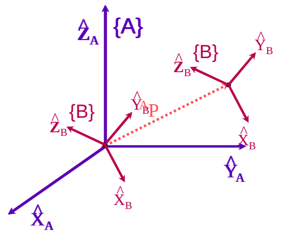
Orientation: $\{^{A}\hat{X}_B, {}^{A}\hat{Y}_B, {}^{A}\hat{Z}_B\}$

describes rotations of {B} with respect to {A}

→ **Rotation Matrix**

Rotation Matrix

$$ {}^{A}_{B}R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} $$

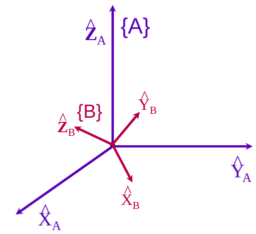


$$ {}^{A}\hat{X}_B = {}^{A}_{B}R\, {}^{B}\hat{X}_B $$

$$ {}^{A}\hat{X}_B = {}^{A}_{B}R \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad {}^{A}\hat{Y}_B = {}^{A}_{B}R \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \quad {}^{A}\hat{Z}_B = {}^{A}_{B}R \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \Rightarrow {}^{A}_{B}R = \begin{bmatrix} {}^{A}\hat{X}_B & {}^{A}\hat{Y}_B & {}^{A}\hat{Z}_B \end{bmatrix} $$

Rotation Matrix

$$ {}^{A}_{B}R = \begin{bmatrix} {}^{A}\hat{X}_B & {}^{A}\hat{Y}_B & {}^{A}\hat{Z}_B \end{bmatrix} $$



Dot Product

$$ {}^{A}\hat{X}_B = \begin{bmatrix} \hat{X}_B . \hat{X}_A \\ \hat{X}_B . \hat{Y}_A \\ \hat{X}_B . \hat{Z}_A \end{bmatrix} $$

$$ {}^{A}_{B}R = \begin{bmatrix} \hat{X}_B.\hat{X}_A & \hat{Y}_B.\hat{X}_A & \hat{Z}_B.\hat{X}_A \\ \hat{X}_B.\hat{Y}_A & \hat{Y}_B.\hat{Y}_A & \hat{Z}_B.\hat{Y}_A \\ \hat{X}_B.\hat{Z}_A & \hat{Y}_B.\hat{Z}_A & \hat{Z}_B.\hat{Z}_A \end{bmatrix} \quad {}^{B}X_A^T $$

Rotation Matrix

$$ {}^{A}_{B}R = \begin{bmatrix} {}^{A}\hat{X}_B & {}^{A}\hat{Y}_B & {}^{A}\hat{Z}_B \end{bmatrix} = \begin{bmatrix} {}^{B}\hat{X}_A^T \\ {}^{B}\hat{Y}_A^T \\ {}^{B}\hat{Z}_A^T \end{bmatrix} = \begin{bmatrix} {}^{B}\hat{X}_A & {}^{B}\hat{Y}_A & {}^{B}\hat{Z}_A \end{bmatrix}^T = {}^{B}_{A}R^T $$

$$ {}^{A}_{B}R = {}^{B}_{A}R^T $$

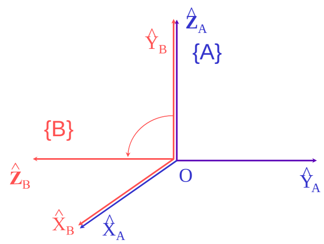
Inverse of Rotation Matrices

$$ {}^{A}_{B}R^{-1} = {}^{B}_{A}R = {}^{A}_{B}R^T $$

$$ {}^{A}_{B}R^{-1} = {}^{A}_{B}R^T $$

Orthonormal Matrix

Example

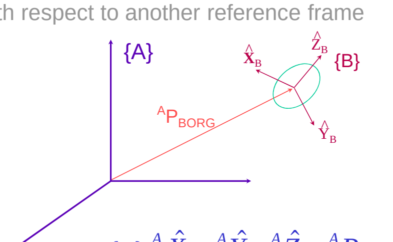


$$ {}^{A}_{B}R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \begin{matrix} \leftarrow {}^{B}\hat{X}_A^T \\ \leftarrow {}^{B}\hat{Y}_A^T \\ \leftarrow {}^{B}\hat{Z}_A^T \end{matrix} $$

$$ \uparrow {}^{A}\hat{X}_B \quad \uparrow {}^{A}\hat{Y}_B \quad \uparrow {}^{A}\hat{Z}_B $$

Description of a Frame

with respect to another reference frame



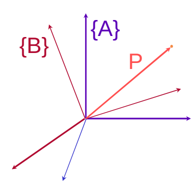
Frame {B}: ${}^{A}\hat{X}_B, {}^{A}\hat{Y}_B, {}^{A}\hat{Z}_B, {}^{A}P_{Borg}$

$$ \{B\} = \{ {}^{A}_{B}R \quad {}^{A}P_{Borg} \} $$

Mapping

changing descriptions from frame to frame

Rotations



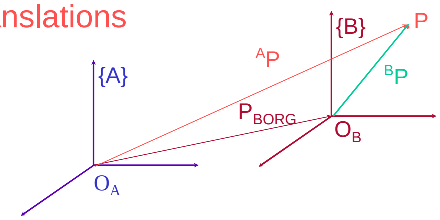
If P is given in {B}: ${}^{B}P$

$$ {}^{A}P = \begin{pmatrix} {}^{B}\hat{X}_A . {}^{B}P \\ {}^{B}\hat{Y}_A . {}^{B}P \\ {}^{B}\hat{Z}_A . {}^{B}P \end{pmatrix} = \begin{pmatrix} {}^{B}\hat{X}_A^T \\ {}^{B}\hat{Y}_A^T \\ {}^{B}\hat{Z}_A^T \end{pmatrix} . {}^{B}P $$

$$ \Downarrow $$

$$ {}^{A}P = {}^{A}_{B}R\, {}^{B}P $$

Translations



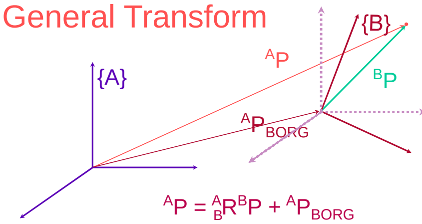
changing the position description of a point P

$\overrightarrow{O_BP} \Rightarrow \overrightarrow{O_AP}$ **(Two different vectors)**

$P_{BORG}: \; P_{O_B} \Rightarrow P_{O_A}$

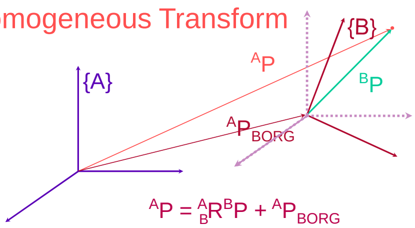
$$P_{O_A} = P_{O_B} + P_{BORG}$$

General Transform



$$^AP = {}^A_BR\,^BP + {}^AP_{BORG}$$

Homogeneous Transform

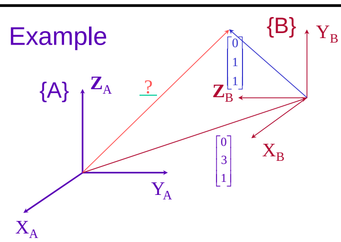


$$^AP = {}^A_BR\,^BP + {}^AP_{BORG}$$

$$\begin{bmatrix} ^AP \\ 1 \end{bmatrix} = \left[\begin{array}{c|c} ^A_BR & ^AP_{Borg} \\ \hline 0\;\;0\;\;0 & 1 \end{array}\right] \begin{bmatrix} ^BP \\ 1 \end{bmatrix}$$

$$\underset{(4x1)}{^AP} = \underset{(4x4)}{^A_BT}\;\underset{(4x1)}{^BP}$$

Example



Homogeneous Transform

$$^A_BT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 3 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad ^BP = \begin{bmatrix} 0 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$^AP = {}^A_BT\,.\,^BP \Rightarrow \; ^AP = \begin{bmatrix} 0 \\ 2 \\ 2 \\ 1 \end{bmatrix}$$

Movie Segment

LittleDog

Learning Locomotion with LittleDog

http://www-clmc.usc.edu

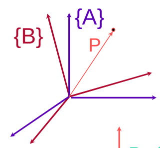
Mrinal Kalakrishnan, Jonas Buchli, Peter Pastor, Michael Mistry, and Stefan Schaal

Operators

Mapping: changing descriptions from frame to frame

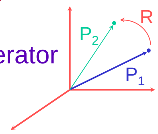
Operators: moving points (within the same frame)

Mapping



$${}^{A}P = {}^{A}_{B}R\,{}^{B}P$$

Rotational Operator



R: $P_1 \longrightarrow P_2$

$$P_2 = R\ P_1$$

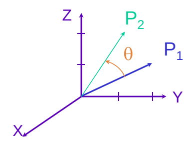
Rotational Operators

$R_K(\theta)$: $P_1 \longrightarrow P_2$

$$P_2 = R_K(\theta)\ P_1$$

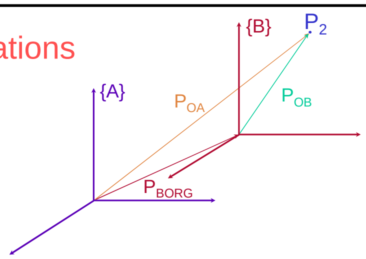
Example

$$R_X(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$



$$P_2 = R_X(\theta)P_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.8 & -0.6 \\ 0 & 0.6 & 0.8 \end{bmatrix} \begin{bmatrix} 0 \\ 2 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 2 \end{bmatrix}$$

Translations

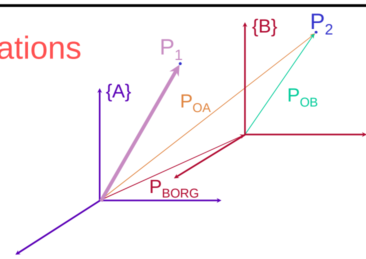


Mapping: P_{BORG} : $P_{OB} \longrightarrow P_{OA}$ (same point)

2 diff. vectors

$$P_{OA} = P_{OB} + P_{BORG}$$

Translations



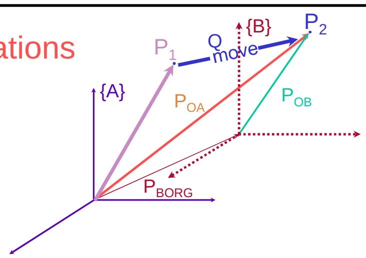
Mapping: P_{BORG} : $P_{OB} \longrightarrow P_{OA}$ (same point)

2 diff. vectors

$$P_{OA} = P_{OB} + P_{BORG}$$

Translational Operator:

Translations



Mapping: P_{BORG} : $P_{OB} \longrightarrow P_{OA}$ (same point)

2 diff. vectors

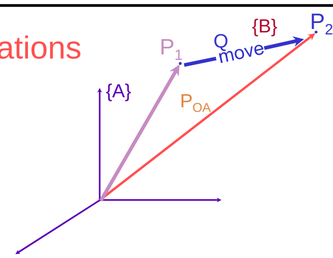
$$P_{OA} = P_{OB} + P_{BORG}$$

Translational Operator:

Q : $P_1 \longrightarrow P_2$ (2 points, 2 diff vectors)

$$P_2 = P_1 + Q$$

Translations

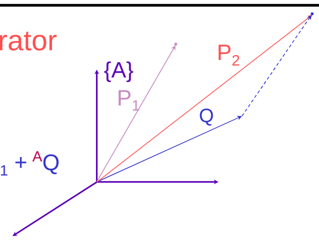


Translational Operator:

Q : $P_1 \longrightarrow P_2$ (2 points, 2 diff vectors)

$$P_2 = P_1 + Q$$

Translation Operator

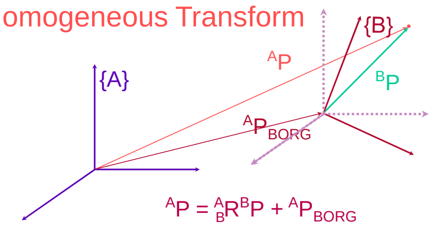


Operator: $^AP_2 = {}^AP_1 + {}^AQ$

Homogeneous Transform:

$$D_Q = \begin{bmatrix} 1 & 0 & 0 & q_x \\ 0 & 1 & 0 & q_y \\ 0 & 0 & 1 & q_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \Rightarrow {}^AP_2 = {}^AD_Q\,{}^AP_1$$

Homogeneous Transform



$$^AP = {}^A_BR\,{}^BP + {}^AP_{BORG}$$

$$\begin{bmatrix} ^AP \\ 1 \end{bmatrix} = \begin{bmatrix} {}^A_BR & {}^AP_{Borg} \\ 0\ 0\ 0 & 1 \end{bmatrix} \begin{bmatrix} ^BP \\ 1 \end{bmatrix}$$

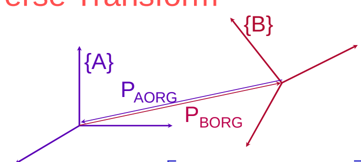
$$\underset{(4\times1)}{^AP} = \underset{(4\times4)}{{}^A_BT}\ \underset{(4\times1)}{^BP}$$

General Operators

$$P_2 = \begin{pmatrix} R_K(\theta) & Q \\ 0\ \ 0\ \ 0 & 1 \end{pmatrix} P_1$$

$$P_2 = T\,P_1$$

Inverse Transform



$${}^A_BT = \begin{bmatrix} {}^A_BR & {}^AP_{Borg} \\ 0\ \ 0\ \ 0 & 1 \end{bmatrix}$$

$R^{-1} = R^T \quad (T^{-1} \neq T^T)$

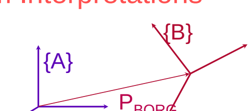
$^BP_{AORG}$

$${}^A_BT^{-1} = {}^B_AT = \begin{bmatrix} {}^A_BR^T & -{}^A_BR^T \cdot {}^AP_{Borg} \\ 0\ \ 0\ \ 0 & 1 \end{bmatrix}$$

Homogeneous Transform Interpretations

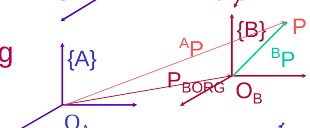
Description of a frame

${}^A_BT$: $\{B\} = \{{}^A_BR \quad {}^AP_{Borg}\}$



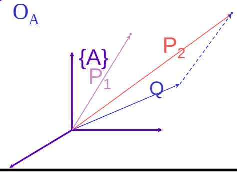
Transform mapping

${}^A_BT: \ {}^BP \rightarrow {}^AP$

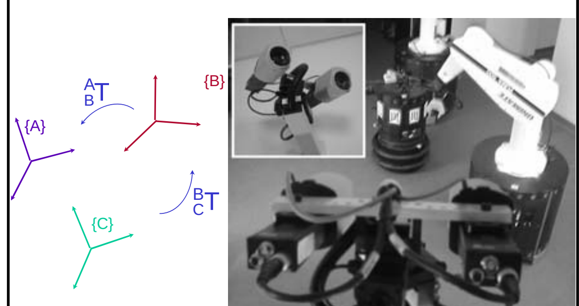


Transform operator

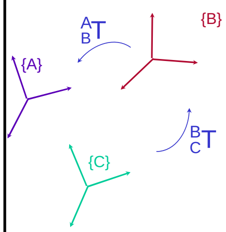
$T: \ P_1 \rightarrow P_2$



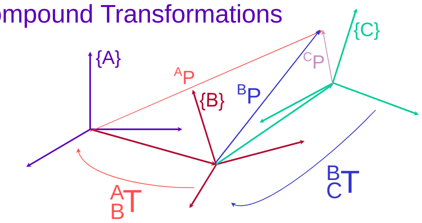
Transform Equation



Transform Equation



Compound Transformations



$${}^BP = {}^B_CT\,{}^CP$$

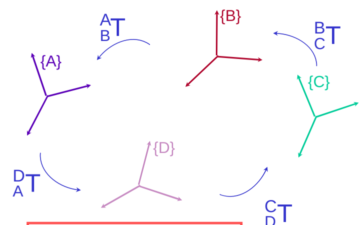
$${}^AP = {}^A_BT\,{}^BP$$

$${}^AP = {}^A_BT\,{}^B_CT\,{}^CP \Rightarrow {}^A_CT = {}^A_BT\,{}^B_CT$$

$${}^A_CT = {}^A_BT\,{}^B_CT$$

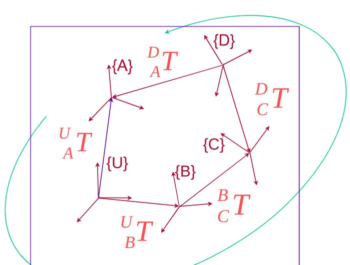
$${}^A_CT = \begin{bmatrix} {}^A_BR\,{}^B_CR & {}^A_BR\,{}^BP_{Corg} + {}^AP_{Borg} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix}$$

Transform Equation



$${}^A_BT\,{}^B_CT\,{}^C_DT\,{}^D_AT \equiv I$$

$$\Rightarrow {}^B_AT = {}^B_CT\,{}^C_DT\,{}^D_AT$$



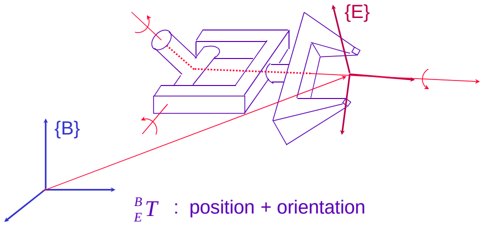
$${}^D_AT^{-1}\cdot{}^D_CT\cdot{}^B_CT^{-1}\cdot{}^U_BT^{-1}\cdot{}^U_AT \equiv I$$

$${}^U_AT = {}^U_BT\cdot{}^B_CT\cdot{}^D_CT^{-1}\cdot{}^D_AT$$

Spatial Descriptions

- Task Description
- Transformations
- Representations ⇐

End-Effector Configuration



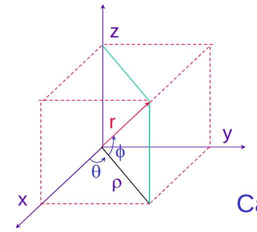
${}^{B}_{E}T$: position + orientation

End-Effector Configuration Parameters

$$X = \begin{bmatrix} X_P \\ X_R \end{bmatrix}$$

X_P ← position
X_R ← orientation

Position Representations



Cartesian: (x, y, z)

Cylindrical: (ρ, θ, z)

Spherical: (r, θ, ϕ)

Rotation Representations

Rotation Matrix

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{r}_3 \end{bmatrix}$$

Direction Cosines

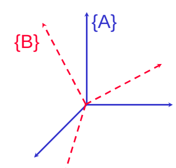
$$x_r = \begin{bmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \\ \mathbf{r}_3 \end{bmatrix}_{(9x1)}$$

<u>**Constraints**</u>

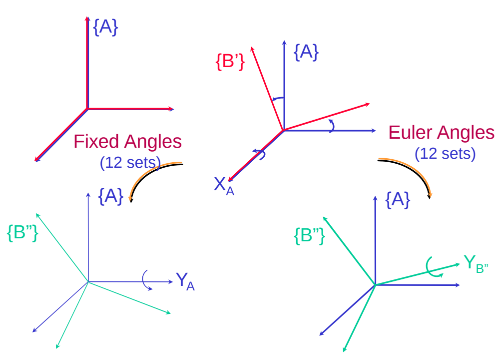
$$|\mathbf{r}_1| = |\mathbf{r}_2| = |\mathbf{r}_3| = 1$$

$$\mathbf{r}_1.\mathbf{r}_2 = \mathbf{r}_1.\mathbf{r}_3 = \mathbf{r}_2.\mathbf{r}_3 = 0$$

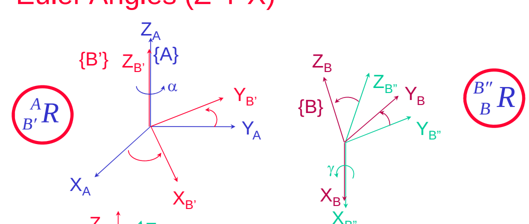
Three Angle Representations

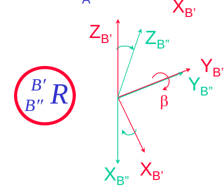


Three Angle Representations



Euler Angles (Z-Y-X)

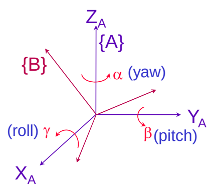




$${}^{A}_{B}R = {}^{A}_{B'}R.\,{}^{B'}_{B''}R.\,{}^{B''}_{B}R$$

$${}^{A}_{B}R = R_Z(\alpha).R_Y(\beta).R_X(\gamma)$$

X-Y-Z Fixed Angles



$R_X(\gamma)$: $v \rightarrow R_X(\gamma).v$

$R_Y(\beta)$: $(R_X(\gamma).v) \rightarrow R_Y(\beta).(R_X(\gamma).v)$

$R_Z(\alpha)$: $(R_Y(\beta).R_X(\gamma).v) \rightarrow R_Z(\alpha).(R_Y(\beta).R_X(\gamma).v)$

$$\boxed{{}^A_BR = {}^A_BR_{XYZ}(\gamma,\beta,\alpha) = R_Z(\alpha).R_Y(\beta).R_X(\gamma)}$$

Z-Y-X Euler Angles

$${}^A_BR = R_{Z'}(\alpha).R_{Y'}(\beta).R_{X'}(\gamma)$$

$$\begin{bmatrix} c\alpha & -s\alpha & 0 \\ s\alpha & c\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{bmatrix}$$

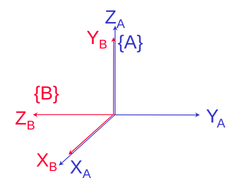
$${}^A_BR = {}^A_BR_{Z'Y'X'}(\alpha,\beta,\gamma) = \begin{bmatrix} c\alpha.c\beta & X & X \\ s\alpha.c\beta & X & X \\ -s\beta & c\beta.s\gamma & c\beta.c\gamma \end{bmatrix}$$

Z-Y-Z Euler Angles

$${}^A_BR = R_{Z'}(\alpha).R_{Y'}(\beta).R_{Z'}(\gamma)$$

$${}^A_BR = {}^A_BR_{Z'Y'Z'}(\alpha,\beta,\gamma) = \begin{bmatrix} X & X & c\alpha.s\beta \\ X & X & s\alpha.s\beta \\ -s\beta.c\gamma & s\beta.s\gamma & c\beta \end{bmatrix}$$

Example



$R_{Z'Y'X'}(\alpha,\beta,\gamma)$: $\alpha = 0$

$\beta = 0$

$\gamma = 90^o$

Fixed & Euler Angles

X-Y-Z Fixed Angles

$$R_{XYZ}(\gamma,\beta,\alpha) = R_Z(\alpha).R_Y(\beta).R_X(\gamma)$$

Z-Y-X Euler Angles

$$R_{Z'Y'X'}(\alpha,\beta,\gamma) = R_Z(\alpha).R_Y(\beta).R_X(\gamma)$$

$$\boxed{R_{Z'Y'X'}(\alpha,\beta,\gamma) = R_{XYZ}(\gamma,\beta,\alpha)}$$

Inverse Problem

Given ${}^A_BR$ find (α,β,γ)

$R_{Z'Y'X'}$

$${}^A_BR = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = \begin{bmatrix} c\alpha.c\beta & c\alpha.s\beta.s\gamma - s\alpha.c\gamma & c\alpha.s\beta.c\gamma + s\alpha.s\gamma \\ s\alpha.c\beta & s\alpha.s\beta.s\gamma + c\alpha.c\gamma & s\alpha.s\beta.c\gamma - c\alpha.s\gamma \\ -s\beta & c\beta.s\gamma & c\beta.c\gamma \end{bmatrix}$$

$$\left.\begin{array}{r} \cos\beta = c\beta = \sqrt{r_{11}^2 + r_{21}^2} \\ \sin\beta = s\beta = -r_{31} \end{array}\right\} \rightarrow \beta = A\tan 2(-r_{31}, \sqrt{r_{11}^2 + r_{21}^2})$$

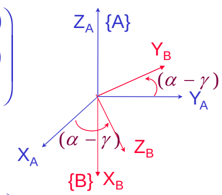
if $c\beta = 0$ $(\beta = \pm 90^o)$ ⇨ Singularity of the representation

⇨ Only $(\alpha + \gamma)$ or $(\alpha - \gamma)$ is defined

Singularities - Example $(R_{Z'Y'X'})$

$c\beta = 0,\ s\beta = +1$

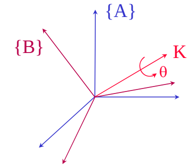
$${}^{A}_{B}R = \begin{pmatrix} 0 & -s(\alpha-\gamma) & c(\alpha-\gamma) \\ 0 & c(\alpha-\gamma) & s(\alpha-\gamma) \\ -1 & 0 & 0 \end{pmatrix}$$



$c\beta = 0,\ s\beta = -1$

$${}^{A}_{B}R = \begin{pmatrix} 0 & -s(\alpha+\gamma) & -c(\alpha+\gamma) \\ 0 & c(\alpha+\gamma) & -s(\alpha+\gamma) \\ 1 & 0 & 0 \end{pmatrix}$$

Equivalent angle-axis representation, $R_K(\theta)$



$$X_r = \theta.K = \begin{bmatrix} \theta.k_X \\ \theta.k_Y \\ \theta.k_Z \end{bmatrix}$$

$$R_K(\theta) = \begin{bmatrix} k_x.k_x.v\theta + c\theta & k_x.k_y.v\theta - k_z.s\theta & k_x.k_z.v\theta + k_y.s\theta \\ k_x.k_y.v\theta + k_z.s\theta & k_y.k_y.v\theta + c\theta & k_y.k_z.v\theta - k_x.s\theta \\ k_x.k_z.v\theta - k_y.s\theta & k_y.k_z.v\theta + k_x.s\theta & k_z.k_z.v\theta + c\theta \end{bmatrix}$$

with $v\theta = 1 - c\theta$

$$R_K(\theta) = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

$$\theta = Ar\cos\left(\frac{r_{11} + r_{22} + r_{33} - 1}{2}\right)$$

$${}^{A}K = \frac{1}{2.\sin\theta} \begin{bmatrix} r_{32} - r_{23} \\ r_{13} - r_{31} \\ r_{21} - r_{12} \end{bmatrix}, \quad \text{singularity for } \sin\theta = 0$$

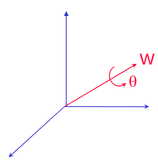
Euler Parameters

$$\varepsilon_1 = W_x.\sin\frac{\theta}{2}$$

$$\varepsilon_2 = W_y.\sin\frac{\theta}{2}$$

$$\varepsilon_3 = W_z.\sin\frac{\theta}{2}$$

$$\varepsilon_4 = \cos\frac{\theta}{2}$$



Normality Condition

$$|W| = 1, \quad \varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 + \varepsilon_4^2 = 1$$

ε : point on a unit hypershpere in four-dimensional space

Inverse Problem Given ${}^{A}_{B}R$ find ε

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \equiv \begin{bmatrix} 1-2\varepsilon_2^2-2\varepsilon_3^2 & 2(\varepsilon_1\varepsilon_2-\varepsilon_3\varepsilon_4) & 2(\varepsilon_1\varepsilon_3+\varepsilon_2\varepsilon_4) \\ 2(\varepsilon_1\varepsilon_2+\varepsilon_3\varepsilon_4) & 1-2\varepsilon_1^2-2\varepsilon_3^2 & 2(\varepsilon_2\varepsilon_3-\varepsilon_1\varepsilon_4) \\ 2(\varepsilon_1\varepsilon_3-\varepsilon_2\varepsilon_4) & 2(\varepsilon_2\varepsilon_3+\varepsilon_1\varepsilon_4) & 1-2\varepsilon_1^2-2\varepsilon_2^2 \end{bmatrix}$$

$$r_{11} + r_{22} + r_{33} = 3 - 4(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2)$$

$$(1 - \varepsilon_4^2)$$

$$\varepsilon_4 = \frac{1}{2}\sqrt{1 + r_{11} + r_{22} + r_{33}}$$

$$\varepsilon_1 = \frac{r_{32} - r_{23}}{4\varepsilon_4}, \quad \varepsilon_2 = \frac{r_{13} - r_{31}}{4\varepsilon_4}, \quad \varepsilon_3 = \frac{r_{21} - r_{12}}{4\varepsilon_4}$$

$\varepsilon_4 = 0?$

Lemma

For all rotations one of the Euler Parameters is greater than or equal to 1/2

$$\left(\sum_{1}^{4} \varepsilon_i^2 = 1\right)$$

Algorithm

Solve with respect to $\max_i\{\varepsilon_i\}$

- $\varepsilon_1 = \max_i\{\varepsilon_i\}$

$$\varepsilon_1 = \frac{1}{2}\sqrt{r_{11} - r_{22} - r_{33} + 1}$$

$$\varepsilon_2 = \frac{(r_{21} + r_{12})}{4\varepsilon_1}, \quad \varepsilon_3 = \frac{(r_{31} + r_{13})}{4\varepsilon_1}, \quad \varepsilon_4 = \frac{(r_{32} - r_{23})}{4\varepsilon_1}$$

- $\varepsilon_1 = \max_i\{\varepsilon_i\}$

$$\varepsilon_1 = \frac{1}{2}\sqrt{r_{11} - r_{22} - r_{33} + 1}$$

- $\varepsilon_2 = \max_i\{\varepsilon_i\}$

$$\varepsilon_2 = \frac{1}{2}\sqrt{-r_{11} + r_{22} - r_{33} + 1}$$

- $\varepsilon_3 = \max_i\{\varepsilon_i\}$

$$\varepsilon_3 = \frac{1}{2}\sqrt{-r_{11} - r_{22} + r_{33} + 1}$$

- $\varepsilon_4 = \max_i\{\varepsilon_i\}$

$$\varepsilon_4 = \frac{1}{2}\sqrt{1 + r_{11} + r_{22} + r_{33}}$$

Euler Parameters / Euler Angles

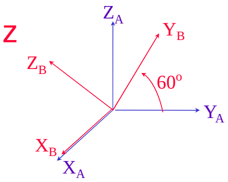
$$\varepsilon_1 = \sin\frac{\beta}{2}\cos\frac{\alpha-\gamma}{2}$$

$$\varepsilon_2 = \sin\frac{\beta}{2}\sin\frac{\alpha-\gamma}{2}$$

$$\varepsilon_3 = \cos\frac{\beta}{2}\sin\frac{\alpha+\gamma}{2}$$

$$\varepsilon_4 = \cos\frac{\beta}{2}\cos\frac{\alpha+\gamma}{2}$$

Quiz



Euler Parameters

$$x_r = \begin{bmatrix} 1/2 \\ 0 \\ 0 \\ \sqrt{3}/2 \end{bmatrix}$$

Direction Cosines

$$x_r = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 1/2 \\ \sqrt{3}/2 \\ 0 \\ -\sqrt{3}/2 \\ 1/2 \end{bmatrix} \begin{matrix} \\ r_1 \\ \\ \\ r_2 \\ \\ \\ r_3 \\ \\ \end{matrix}$$