

SDM5008 Advanced Control for Robotics

Lecture 1: Rigid Body Configuration and Velocity

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Outline

- Rigid Body Configuration
- Rigid Body Velocity (Twist)
- Geometric Aspect of Twist: Screw Motion

Free Vector

- **Free Vector:** geometric quantity with length and direction



- Given a reference frame, v can be moved to a position such that the base of the arrow is at the origin without changing the orientation. Then the vector v can be represented by its coordinates v in the reference frame.



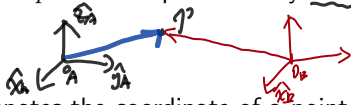
- v denotes the physical quantity while ${}^A v$ denote its coordinate wrt frame $\{A\}$.

Point

- **Point:** p denotes a point in the physical space

• p

- A point p can be represented by a vector from frame origin to p



$${}^A p \triangleq {}^A(\vec{O_A p}), \quad {}^B p = {}^B(\vec{O_B p})$$

- ${}^A p$ denotes the coordinate of a point p wrt frame $\{A\}$ ${}^B(\vec{O_A p})$

- When left-superscript is not present, it means the physical vector itself or the coordinate of the vector for which the reference frame is clear from the context.

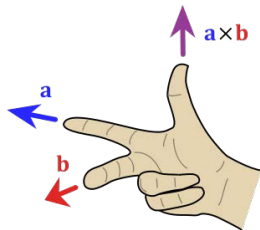
Cross Product

- **Cross product** or **vector product** of $a \in \mathbb{R}^3, b \in \mathbb{R}^3$ is defined as

$$\underline{a \times b} = \begin{bmatrix} a_2 b_3 - a_3 b_2 \\ a_3 b_1 - a_1 b_3 \\ a_1 b_2 - a_2 b_1 \end{bmatrix} = \begin{bmatrix} 0 & -a_3 & -a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \quad (1)$$

Properties:

- $\|a \times b\| = \|a\| \|b\| \sin(\theta)$
- $a \times b = -b \times a$
- $a \times a = 0$



Skew symmetric representation

- It can be directly verified from definition that $a \times b = [a]b$, where

$$[a] \triangleq \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix} \quad (2)$$

- $a = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \leftrightarrow [a]$
- $[a] = -[a]^T$ (called skew symmetric)
- $[a][b] - [b][a] = [a \times b]$ (Jacobi's identity)

Rotation Matrix

- **Frame:** 3 coordinate vectors (unit length) $\hat{x}, \hat{y}, \hat{z}$, and an origin
 - $\hat{x}, \hat{y}, \hat{z}$ mutually orthogonal
 - $\hat{x} \times \hat{y} = \hat{z}$
- **Rotation Matrix:** specifies orientation of one frame relative to another

$${}^A R_B = \begin{bmatrix} {}^A \hat{x}_B & {}^A \hat{y}_B & {}^A \hat{z}_B \end{bmatrix}$$

- A valid rotation matrix R satisfies: (i) $R^T R = I$; (ii) $\det(R) = 1$

Special Orthogonal Group

- **Special Orthogonal Group:** Space of Rotation Matrices in \mathbb{R}^n is defined as

$$SO(n) = \{R \in \mathbb{R}^{n \times n} : R^T R = I, \det(R) = 1\}$$

- $SO(n)$ is a *group*. We are primarily interested in $SO(3)$ and $SO(2)$, rotation groups of \mathbb{R}^3 and \mathbb{R}^2 , respectively.
- **Group** is a set G , together with an operation \bullet , satisfying the following group axioms:
 - **Closure:** $a \in G, b \in G \Rightarrow a \bullet b \in G$
 - **Associativity:** $(a \bullet b) \bullet c = a \bullet (b \bullet c), \forall a, b, c \in G$
 - **Identity element:** $\exists e \in G$ such that $e \bullet a = a$, for all $a \in G$.
 - **Inverse element:** For each $a \in G$, there is a $b \in G$ such that $a \bullet b = b \bullet a = e$, where e is the identity element.

Use of Rotation Matrix (1/2)

- Representing an orientation ${}^A R_B$
- Changing the reference frame ${}^A R_B$:

Use of Rotation Matrix (2/2)

- Rotating a vector or a frame $\text{Rot}(\hat{\omega}, \theta)$: will be discussed in next lecture.

Rigid Body Configuration

- Given two coordinate frames $\{A\}$ and $\{B\}$, the configuration of B relative to A is determined by
 - ${}^A R_B$ and ${}^A O_B$
- For a (free) vector r , its coordinates ${}^A r$ and ${}^B r$ are related by:
- For a point p , its coordinates ${}^A p$ and ${}^B p$ are related by:

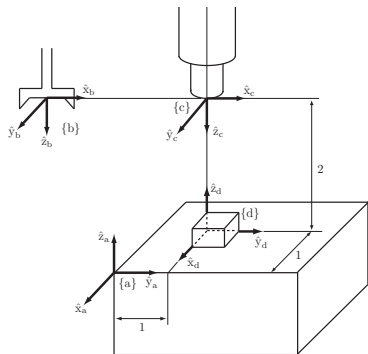
Homogeneous Transformation Matrix

- **Homogeneous Transformation Matrix:** ${}^A T_B$

- Homogeneous coordinates:

Example of Homogeneous Transformation Matrix

Fixed frame $\{a\}$; end effector frame $\{b\}$, the camera frame $\{c\}$, and the workpiece frame $\{d\}$. Suppose $\|p_c - p_b\| = 4$



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Rigid Body Velocity (1/3)

- Consider a rigid body in motion. The body has infinitely many points $\{p_i\}$ with different velocities $\{v_{p_i}\}$
 - All these velocities v_{p_i} 's are not independent
 - They can be expressed by the same set of parameter
 - Rigid body velocity (i.e. spatial velocity, twist) is one such parameterization

Rigid Body Velocity (3/3)

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Rigid Body Velocity: Spatial Velocity (Twist)

- How to represent a rigid body velocity?
 - Pick an arbitrary point r (reference point), which may or may not be body-fixed
 - Define v_r as the velocity of **the body-fixed point currently coincides with** r
 - For any body-fixed point p on the body: $v_p = v_r + \omega \times (\vec{r}\vec{p})$
- **Spatial Velocity (Twist):** $\mathcal{V}_r = (\omega, v_r)$
- Twist is a “physical” quantity (just like linear or angular velocity)
 - It can be represented in any frame for any chosen reference point r
- A rigid body with $\mathcal{V}_r = (\omega, v_r)$ can be “thought of” as translating at v_r while rotating with angular velocity ω about an axis passing through r
 - This is just one way to interpret the motion.

Spatial Velocity Representation in a Reference Frame

- Given frame $\{A\}$ and a spatial velocity \mathcal{V}
- Choose o_A (the origin of $\{A\}$) as the reference point to represent the rigid body velocity

- Coordinates of \mathcal{V} in $\{A\}$:

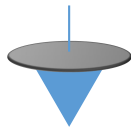
$${}^A\mathcal{V}_{o_A} = ({}^A\omega, {}^A v_{o_A})$$

- By default, we assume the origin of the frame is used as the reference point:

$${}^A\mathcal{V} = {}^A\mathcal{V}_{o_A}$$

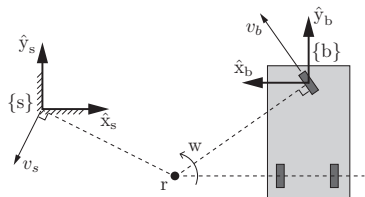
Example of Twist I

- Example I:



Example of Twist II

- Example II:



$$r_s = (2, -1, 0), r_b = (2, -1.4, 0), w=2 \text{ rad/s}$$

Change Reference Frame for Twist (1/2)

- Given a twist \mathcal{V} , let ${}^A\mathcal{V}$ and ${}^B\mathcal{V}$ be their coordinates in frames $\{A\}$ and $\{B\}$

$${}^A\mathcal{V} = \begin{bmatrix} {}^A\omega \\ {}^A v_A \end{bmatrix}, \quad {}^B\mathcal{V} = \begin{bmatrix} {}^B\omega \\ {}^B v_B \end{bmatrix}$$

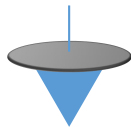
- They are related by ${}^A\mathcal{V} = {}^A X_B {}^B\mathcal{V}$

Change Reference Frame for Twist (2/2)

- If configuration $\{B\}$ in $\{A\}$ is $T = (R, p)$, then

$${}^A X_B = [\text{Ad}_T] \triangleq \begin{bmatrix} R & 0 \\ [p]R & R \end{bmatrix}$$

Example I Revisited

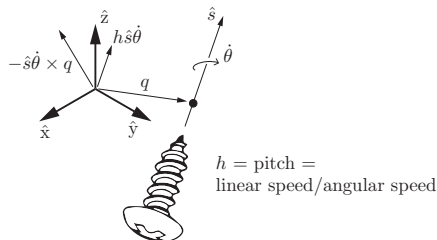


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Screw Motion: Definition

- Rotating about an axis while also translating along the axis



- Represented by screw axis $\{q, \hat{s}, h\}$ and rotation speed $\dot{\theta}$
 - \hat{s} : unit vector in the direction of the rotation axis
 - q : any point on the rotation axis
 - h : **screw pitch** which defines the ratio of the linear velocity along the screw axis to the angular velocity about the screw axis
- Theorem (Chasles): Every rigid body motion can be realized by a screw motion.

From Screw Motion to Twist

- Consider a rigid body under a screw motion with screw axis $\{\hat{s}, h, q\}$ and (rotation) speed $\dot{\theta}$
 - Fix a reference frame $\{A\}$ with origin o_A .
 - Find the twist ${}^A\mathcal{V} = ({}^A\omega, {}^A v_{o_A})$
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- **Result:** given screw axis $\{\hat{s}, h, q\}$ with rotation speed $\dot{\theta}$, the corresponding twist $\mathcal{V} = (\omega, v)$ is given by

$$\omega = \hat{s}\dot{\theta} \quad v = -\hat{s}\dot{\theta} \times q + h\hat{s}\dot{\theta}$$

- The result holds as long as all the vectors and the twist are represented in the same reference frame

From Twist to Screw Motion

- The converse is true as well: given any twist $\mathcal{V} = (\omega, v)$ we can always find the corresponding screw motion $\{q, \hat{s}, h\}$ and $\dot{\theta}$
 - If $\omega = 0$, then it is a pure translation ($h = \infty$)

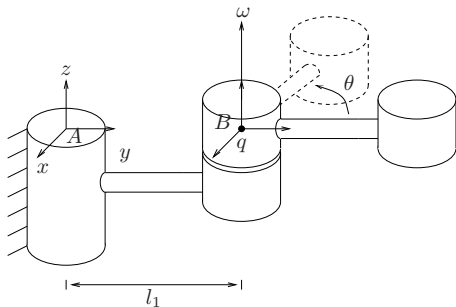
$$\hat{s} = \frac{v}{\|v\|}, \quad \dot{\theta} = \|v\|, \quad h = \infty, \quad q \text{ can be arbitrary}$$

- If $\omega \neq 0$:

$$\hat{s} = \frac{\omega}{\|\omega\|}, \quad \dot{\theta} = \|\omega\|, \quad q = \frac{\omega \times v}{\|\omega\|^2}, \quad h = \frac{\omega^T v}{\|\omega\|}$$

Examples: Screw Axis and Twist

- What is the twist that corresponds to rotating about \hat{z}_B with $\dot{\theta} = 2$?



- What is the screw axis for twist $\mathcal{V} = (0, 2, 2, 4, 0, 0)$?

Screw Representation of a Twist

- Recall: an angular velocity vector ω can be viewed as $\hat{\omega}\dot{\theta}$, where $\hat{\omega}$ is the unit rotation axis and $\dot{\theta}$ is the rate of rotation about that axis
- Similarly, a twist (spatial velocity) \mathcal{V} can be interpreted in terms of a **screw axis** \hat{S} and a velocity $\dot{\theta}$ about the screw axis
- Consider a rigid body motion along a screw axis $\hat{S} = \{\hat{s}, h, q\}$ with speed $\dot{\theta}$. With slight abuse of notation, we will often write its twist as

$$\mathcal{V} = \hat{S}\dot{\theta}$$

- In this notation, we think of \hat{S} as the twist associated with a unit speed motion along the screw axis $\{\hat{s}, h, q\}$

More Discussions