Lecture

Navigation Mathematics: Translation

EE 565: Position, Navigation and Timing

Lecture Notes Update on Spring 2023

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Lecture Topics

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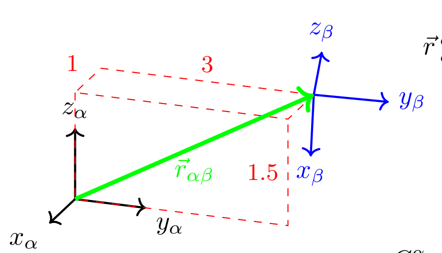
1 Vector Notation for Translation

Translation Between Frames

Define the vector $\vec{r}_{\alpha\beta}$ from the origin of $\{\alpha\}$ to the origin of $\{\beta\}$.

- specifies translation between frames



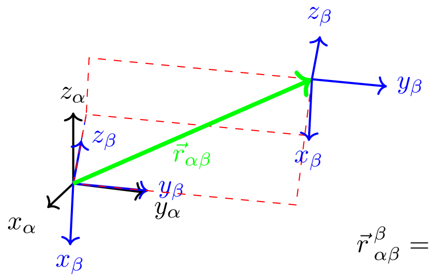
$$\vec{r}^{\,\alpha}_{\alpha\beta} = \begin{bmatrix} x^\alpha_{\alpha\beta} \\ y^\alpha_{\alpha\beta} \\ z^\alpha_{\alpha\beta} \end{bmatrix} = \begin{bmatrix} -1.00 \\ 3 \\ 1.50 \end{bmatrix}$$

$$C^\alpha_\beta = \begin{bmatrix} 0.785 & -0.366 & 0.500 \\ 0.242 & 0.924 & 0.296 \\ -0.571 & -0.111 & 0.813 \end{bmatrix}$$

Now have means (and notation) to describe rotation and translation between coordinate frames. .3

Translation Between Frames

- Resolve, i.e., coordinatize, $\vec{r}_{\alpha\beta}$ *wrt* frame $\{\beta\}$.



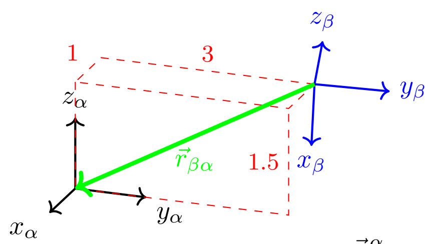
$$\vec{r}^{\,\beta}_{\alpha\beta} = \begin{bmatrix} x^\beta_{\alpha\beta} \\ y^\beta_{\alpha\beta} \\ z^\beta_{\alpha\beta} \end{bmatrix} = C^\beta_\alpha \vec{r}^{\,\alpha}_{\alpha\beta} = \begin{bmatrix} -0.914 \\ 2.97 \\ 1.61 \end{bmatrix}$$

Same vector, so same "direction" and length. .4

Translation Between Frames

Reverse vector $\vec{r}$, i.e., now from origin of $\{\beta\}$ to origin of $\{\alpha\}$.

- notation: $\vec{r}_{\beta\alpha} = -\vec{r}_{\alpha\beta}$



$$\vec{r}^{\,\alpha}_{\beta\alpha} = \begin{bmatrix} x^\alpha_{\beta\alpha} \\ y^\alpha_{\beta\alpha} \\ z^\alpha_{\beta\alpha} \end{bmatrix} = -\vec{r}^{\,\alpha}_{\alpha\beta} = \begin{bmatrix} -(-1.00) \\ -(3) \\ -(1.50) \end{bmatrix}$$

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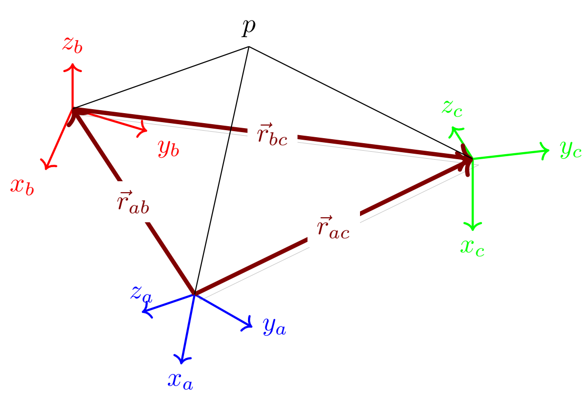
2 Translation Between More Than Two Coordinate Frames

Translation (more than two coordinate frames)

Consider three coordinate systems $\{a\}$, $\{b\}$, $\{c\}$ that have translation and rotation relative to each other.

- Knowing relationships between frames $\{a\}$, $\{b\}$, and $\{c\}$, i.e., $\vec{r}_{ab}$, $\vec{r}_{bc}$, $\vec{r}_{ac}$, C^a_b, C^b_c, and C^a_c, location of point p can be described in any frame, i.e., $\vec{p}^{\,a}$ or $\vec{p}^{\,b}$ or $\vec{p}^{\,c}$.



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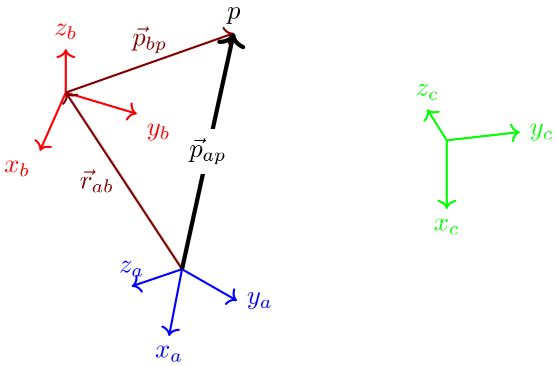
Translation (more than two coordinate frames)

Determine the location of the point p relative to $\{a\}$ given location of point p is known relative to $\{b\}$.

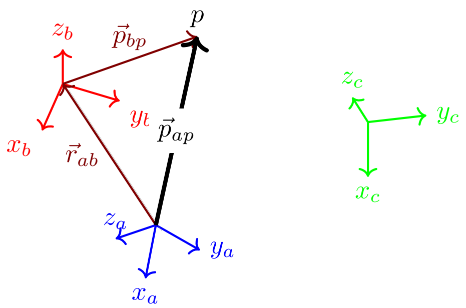


- $\vec{p}_{ap} = \vec{r}_{ab} + \vec{p}_{bp}$ In what frame?
- $\vec{p}^{\,a}_{ap} = \vec{r}^{\,a}_{ab} + \vec{p}^{\,a}_{bp}$ or $\vec{p}^{\,b}_{ap} = \vec{r}^{\,b}_{ab} + \vec{p}^{\,b}_{bp}$ or $\vec{p}^{\,c}_{ap} = \vec{r}^{\,c}_{ab} + \vec{p}^{\,c}_{bp}$

Shorthand notation: $\vec{p}^{\,a} \equiv \vec{p}^{\,a}_{ap}$ .7

Translation (more than two coordinate frames)

Given $\vec{p}^{\,a}_{ap} = \vec{r}^{\,a}_{ab} + \vec{p}^{\,a}_{bp}$ and/or the diagram, how would one find $\vec{p}^{\,b}_{bp}$?



- use given relationship or vector addition
  $\Rightarrow \vec{p}^{\,a}_{bp} = \vec{p}^{\,a}_{ap} - \vec{r}^{\,a}_{ab}$
- now need to reference to $\{b\}$
  $C^b_a \vec{p}^{\,a}_{bp} = C^b_a \left(\vec{p}^{\,a}_{ap} - \vec{r}^{\,a}_{ab}\right)$
  $\Rightarrow \vec{p}^{\,b}_{bp} = \vec{p}^{\,b}_{ap} - \vec{r}^{\,b}_{ab}$ .8

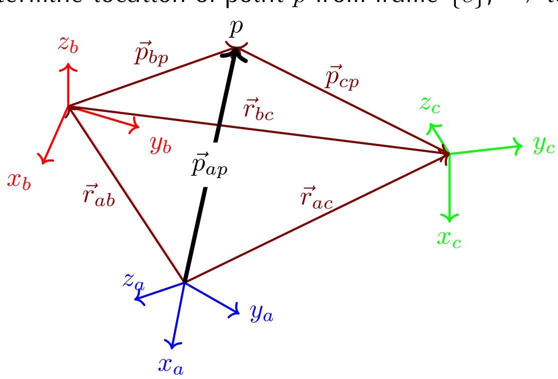
Translation (more than two coordinate frames)

It is important to remember difference between recoordinatizing a vector and finding a location *wrt* a different frame.

- Recoordinatizing: $\vec{p}^{\,c}_{ap} = C^c_a \vec{p}^{\,a}_{ap}$ (only frame of reference changes)
- Location *wrt* different frame: $\vec{p}^{\,c}_{cp} = \vec{r}^{\,c}_{cb} + C^c_b \vec{r}^{\,b}_{ba} + C^c_a \vec{p}^{\,a}_{ap}$ (vector addition in same frame) $\neq C^c_a \vec{p}^{\,a}_{ap}$ .9

Translation (more than two coordinate frames)

Determine location of point p from frame $\{c\}$; $\Rightarrow$ looking for $\vec{p}_{cp}$



Many approaches given labeled vectors/translations.

$\vec{p}_{cp}$

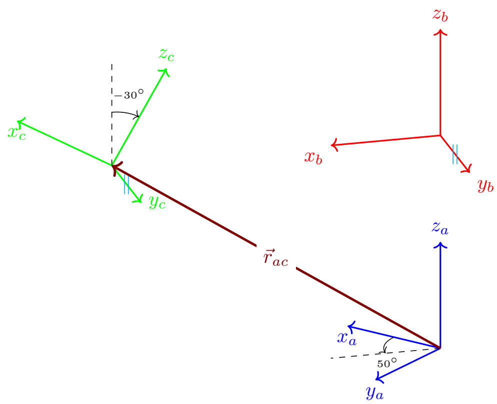
$$= -\vec{r}_{bc} + \vec{p}_{bp}$$
$$= -\vec{r}_{ac} + \vec{r}_{ab} + \vec{p}_{bp}$$
$$= -\vec{r}_{ac} + \vec{p}_{ap}$$

- In what frame? doesn't matter, so long as same
- Can always recoordinatize given C^a_b, C^b_c, C^c_a .10

3 Example

Example - Given

Consider the three coordinate frames $\{a\}, \{b\}, \{c\}$ shown with the rotations and translations between some frames given.



$C_b^a = R_{z,50°}$
$C_c^b = R_{y,-30°}$
$\vec{r}^{\,a}_{ab} = \begin{bmatrix} 0 & 0 & 2 \end{bmatrix}^T$
$\vec{r}^{\,b}_{bc} = \begin{bmatrix} 3 & 0 & 0 \end{bmatrix}^T$

- find
  C_c^a
  $\vec{r}^{\,a}_{ac}$
  $\vec{r}^{\,c}_{ca}$

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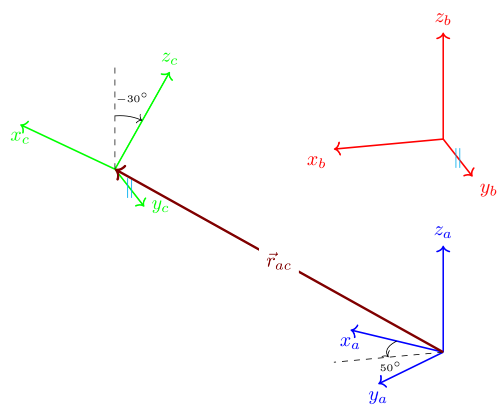
Example - Find C_c^a

$$C_c^a = C_b^a C_c^b = R_{z,50°} R_{y,-30°}$$



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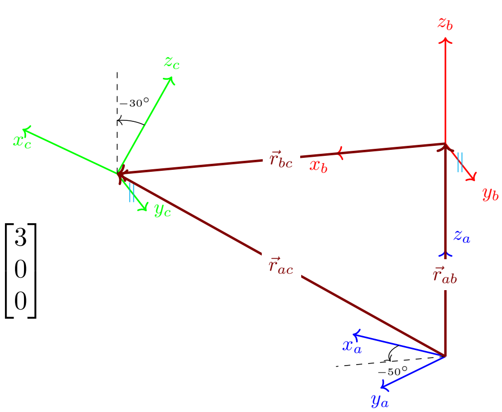
Example - Find $\vec{r}^{\,a}_{ac}$

$$\begin{aligned} \vec{r}^{\,a}_{ac} &= \vec{r}^{\,a}_{ab} + \vec{r}^{\,a}_{bc} \\ &= \vec{r}^{\,a}_{ab} + C_b^a \vec{r}^{\,b}_{bc} \\ &= \begin{bmatrix} 0 \\ 0 \\ 2 \end{bmatrix} + R_{z,50°} \begin{bmatrix} 3 \\ 0 \\ 0 \end{bmatrix} \\ &= \begin{bmatrix} 0 \\ 0 \\ 2 \end{bmatrix} + \begin{bmatrix} \cos 50° & -\sin 50° & 0 \\ \sin 50° & \cos 50° & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 3 \\ 0 \\ 0 \end{bmatrix} \\ &= \begin{bmatrix} 1.93 \\ 2.30 \\ 2.00 \end{bmatrix} \end{aligned}$$



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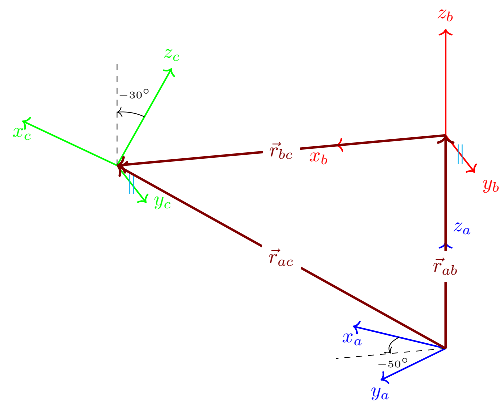
Example - Find $\vec{r}^{\,c}_{ca}$

$$
\begin{aligned}
\vec{r}^{\,c}_{ca} &= -\vec{r}^{\,c}_{ac} \\
&= -C^c_a \vec{r}^{\,a}_{ac} \\
&= -\left[C^a_c\right]^T \vec{r}^{\,a}_{ac} \\
&= -\left[R_{z,50^\circ}\ R_{y,-30^\circ}\right]^T \begin{bmatrix} 1.93 \\ 2.30 \\ 2.00 \end{bmatrix} \\
&= \begin{bmatrix} -3.59 \\ 0 \\ -0.232 \end{bmatrix}
\end{aligned}
$$



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The End

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