The University of California, Los Angeles

Robotics Design Capstone

EE 183DB

Off-center spinning mass controller for Quadcopters

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Abstract

This project is insanely hard...

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1 Symbols

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Here is a list of all symbols used in this paper:

$\boldsymbol{p} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$	linear position vectors
$\boldsymbol{q} = \begin{bmatrix} q_r \\ q_i \\ q_j \\ q_k \end{bmatrix}$	angular orientation in quaternion
$\boldsymbol{F_T}$	thrust force
$\boldsymbol{F_G}$	gravitational force
$\boldsymbol{F_{AB}}$	reaction force acted from A on B
$\boldsymbol{\tau_{AB}}$	reaction torque acted from A on B
$\boldsymbol{\tau_M}$	torque generated by the motor
$\boldsymbol{\tau_{RF}}$	torque generated by the reaction force
m_A	mass of A
I_A	moment of inertial of A
S_x, C_x, T_x	$\sin(x), \cos(x), \tan(x)$ respectively

9 Mathematical Derivation

9.1 Appendix

The Quaternion-derived Rotation matrix is defined as follow,

$$
{}^{O}_{B}R = R(\boldsymbol{q_B}) = \begin{bmatrix} q_r^2 + q_i^2 - q_j^2 - q_k^2 & 2q_iq_j - 2q_rq_k & 2q_iq_k + 2q_rq_j \\ 2q_iq_j + 2q_rq_k & q_r^2 - q_i^2 + q_j^2 - q_k^2 & 2q_jq_k - 2q_rq_i \\ 2q_iq_k - 2q_rq_j & 2q_jq_k + 2q_rq_i & q_r^2 - q_i^2 - q_j^2 + q_k^2 \end{bmatrix}
$$

9.2 Quadcopter Body Dynamics

Forces and Torques:

$$
{}^{B}\boldsymbol{F_T} = \begin{bmatrix} 0 \\ 0 \\ F_{TB} \end{bmatrix}
$$

$$
{}^{O}\boldsymbol{F_{GB}} = \begin{bmatrix} 0 \\ 0 \\ -m_b g \end{bmatrix}
$$

$$
{}^{O}\boldsymbol{F_{CB}} = \begin{bmatrix} F_{CBx} \\ F_{CBy} \\ F_{CBz} \end{bmatrix}
$$

$$
{}^{B}\boldsymbol{\tau_{CB}} = \begin{bmatrix} \tau_{CBx} \\ \tau_{CBy} \\ -\tau_M \end{bmatrix}
$$

Net Force and Torque

$$
{}^{O}\boldsymbol{F_{B,net}} = {}^{O}\boldsymbol{F_{GB}} + {}^{O}\boldsymbol{F_T} + {}^{O}\boldsymbol{F_{CB}} = m_B\, {}^{O}\boldsymbol{a_B} \tag{1}
$$

$$
{}^{O}\boldsymbol{\tau_{B,net}} = R(\boldsymbol{q_B})\, {}^{B}\boldsymbol{\tau_{CB}} = {}^{O}I_B\, {}^{O}\boldsymbol{\alpha_B} \tag{2}
$$

9.3 Controller Dynamics

Forces and Torques:

$$
\begin{gathered}
{}^{O}\boldsymbol{F_{BC}} = \begin{bmatrix} F_{BCx} \\ F_{BCy} \\ F_{BCz} \end{bmatrix} \\
{}^{O}\boldsymbol{F_{GC}} = \begin{bmatrix} 0 \\ 0 \\ -m_c g \end{bmatrix} \\
{}^{C}\boldsymbol{\tau_{BC}} = \begin{bmatrix} \tau_{BCx} \\ \tau_{BCy} \\ \tau_{M} \end{bmatrix} \\
{}^{O}\boldsymbol{r_{CB}} = R(\boldsymbol{q_C}) \begin{bmatrix} -L_{Mx} \\ 0 \\ -L_{Mz} \end{bmatrix} \\
{}^{O}\boldsymbol{\tau_{RF}} = {}^{O}\boldsymbol{r_{CB}} \times {}^{O}\boldsymbol{F_{BC}}
\end{gathered}
$$

Net Force and Net Torque:

$$
{}^{O}\boldsymbol{F_{net,C}} = {}^{O}\boldsymbol{F_{BC}} + {}^{O}\boldsymbol{F_{GC}} = m_C\, {}^{O}\boldsymbol{a_C} \tag{3}
$$

$$
{}^{O}\boldsymbol{\tau_{net,C}} = R(\boldsymbol{q_C})\, {}^{C}\boldsymbol{\tau_{BC}} + {}^{O}\boldsymbol{\tau_{RF}} = {}^{O}I_c\, {}^{O}\boldsymbol{\alpha_C} \tag{4}
$$

9.4 Constraints and Manipulation

In the derivation below, assume everything is in the inertial frame unless explicitly stated.

The two bodies are contrainted (attached together), there are some relationship between the states and the forces between the body and the controller,

Let $\boldsymbol{p_{sys}} = \boldsymbol{p_B}$ and $\boldsymbol{q_{sys}} = \boldsymbol{q_B}$,

$$
\begin{bmatrix} \boldsymbol{p_C} \\ \boldsymbol{q_C} \end{bmatrix} = \begin{bmatrix} \boldsymbol{p_B} + \boldsymbol{r_{BC}} \\ \boldsymbol{q_\theta q_B} \end{bmatrix} = \begin{bmatrix} \boldsymbol{p_{sys}} + \boldsymbol{r_{BC}} \\ \boldsymbol{q_\theta q_{sys}} \end{bmatrix} \tag{5}
$$

$$
\begin{bmatrix} \boldsymbol{\dot{p}_C} \\ \boldsymbol{\dot{q}_C} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\dot{p}_{sys}} + \dot{R}(\boldsymbol{q_{sys}})\, {}^{B}\boldsymbol{r_{BC}} \\ \boldsymbol{q_\theta \dot{q}_{sys}} + \boldsymbol{\dot{q}_\theta q_{sys}} \end{bmatrix} \tag{6}
$$

$$
\begin{bmatrix} \boldsymbol{\ddot{p}_C} \\ \boldsymbol{\ddot{q}_C} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\ddot{p}_{sys}} + \ddot{R}(\boldsymbol{q_{sys}})\, {}^{B}\boldsymbol{r_{BC}} \\ \boldsymbol{q_\theta \ddot{q}_{sys}} + 2[\boldsymbol{\dot{q}_\theta \dot{q}_{sys}}] + \boldsymbol{\ddot{q}_\theta q_{sys}} \end{bmatrix} \tag{7}
$$

Newton's Third Law

$$^{O}\boldsymbol{F_{BC}} = -\,^{O}\boldsymbol{F_{CB}} \tag{8}$$

$$^{O}\boldsymbol{\tau_{BC}} = -\,^{O}\boldsymbol{\tau_{CB}} \tag{9}$$

To limit our degree of freedom in the system, we have set a constraint for our quaternions, namely unit quaternion:

$$q_r^2 + q_i^2 + q_j^2 + q_k^2 = 1 \tag{10}$$

$$q_r\dot{q}_r + q_i\dot{q}_i + q_j\dot{q}_j + q_k\dot{q}_k = 0 \tag{11}$$

$$q_r\ddot{q}_r + q_i\ddot{q}_i + q_j\ddot{q}_j + q_k\ddot{q}_k + \dot{q}_r{}^2 + \dot{q}_i{}^2 + \dot{q}_j{}^2 + \dot{q}_k{}^2 = 0 \tag{12}$$

Last but not least, in the derivation below we use $\boldsymbol{q_\theta}$ directly for ease of typsetting, however, q_θ is not our state variable but θ, their relationship is defined below

$$\boldsymbol{q_\theta} = \cos(\frac{\theta}{2}) + \sin(\frac{\theta}{2})R(\boldsymbol{q_{sys}})\,^{B}\hat{\boldsymbol{z_B}}$$

$$\dot{\boldsymbol{q}}_{\boldsymbol{\theta}} = -\frac{1}{2}\sin(\frac{\theta}{2})\dot{\theta} + \frac{1}{2}\cos(\frac{\theta}{2})\dot{\theta}R(\boldsymbol{q_{sys}})\,^{B}\hat{\boldsymbol{z_B}} + \sin(\frac{\theta}{2})R(\dot{\boldsymbol{q}}_{\boldsymbol{sys}})\,^{B}\hat{\boldsymbol{z_B}}$$

where $^{B}\hat{\boldsymbol{z_B}} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$

9.4.1 Combining the Force equations

From (1),

$$^{O}\boldsymbol{F_{CB}} = m_B\,^{O}\boldsymbol{a_B} - \,^{O}\boldsymbol{F_{GB}} - \,^{O}\boldsymbol{F_T}$$

From (3),

$$^{O}\boldsymbol{F_{BC}} = m_C\,^{O}\boldsymbol{a_C} - \,^{O}\boldsymbol{F_{GC}}$$

Using (6),

$$m_B\,^{O}\boldsymbol{a_B} + m_C\,^{O}\boldsymbol{a_C} = \,^{O}\boldsymbol{F_{GC}} + \,^{O}\boldsymbol{F_{GB}} + \,^{O}\boldsymbol{F_T}$$

Simplifying the above expression, we get

$$(m_b + m_c)\ddot{\boldsymbol{p}}_{\boldsymbol{sys}} + m_c\ddot{R}(\boldsymbol{q_{sys}})\,^{B}\boldsymbol{r_{BC}} = \boldsymbol{F_{GC}} + \boldsymbol{F_{GB}} + \boldsymbol{F_T} \tag{13}$$

9.4.2 Combining the Torqe equations

From (2),

$$ {}^{O}\boldsymbol{\tau_{CB}} = {}^{O}I_B\, {}^{O}\boldsymbol{\alpha_B} $$

From (4),

$$ {}^{O}\boldsymbol{\tau_{BC}} = {}^{O}I_c\, {}^{O}\boldsymbol{\alpha_C} - {}^{O}\boldsymbol{\tau_{RF}} $$

Using (7),

$$ {}^{O}I_B\, {}^{O}\boldsymbol{\alpha_B} + {}^{O}I_c\, {}^{O}\boldsymbol{\alpha_C} = {}^{O}\boldsymbol{\tau_{RF}} $$

Assuming all the vectors are represented in the inertial O frame, using the quaternion representation for angular acceleration,

$$ 2I_B\left[\boldsymbol{\ddot{q}_B q_B^*} - (\boldsymbol{\dot{q}_B q_B^*})^2\right] + 2I_c\left[\boldsymbol{\ddot{q}_C q_C^*} - (\boldsymbol{\dot{q}_C q_C^*})^2\right] = {}^{O}\boldsymbol{\tau_{RF}} \tag{14} $$

Substituting (5)-(7) in the above expression and isolating second derivative on the left, we have

$$ 2I_B[\boldsymbol{\ddot{q}_{sys} q_{sys}^*}] + 2I_C[\boldsymbol{q_\theta \ddot{q}_{sys}}(\boldsymbol{q_\theta q_{sys}})^*] + 2I_C[\boldsymbol{\ddot{q}_\theta q_{sys}}](\boldsymbol{q_\theta q_{sys}})^* - \boldsymbol{r_{CB}} \times \boldsymbol{F_{BC}} = \zeta \tag{15} $$

where

$$ \zeta = 2I_B(\boldsymbol{\dot{q}_{sys} q_{sys}^*})^2 + 2I_C[(\boldsymbol{q_\theta \dot{q}_{sys}} + \boldsymbol{\dot{q}_\theta q_{sys}})(\boldsymbol{q_\theta q_{sys}})^*]^2 - 4I_C(\boldsymbol{\dot{q}_\theta \dot{q}_{sys}})(\boldsymbol{q_\theta q_{sys}})^* $$

Note that we put $\boldsymbol{\tau_{RF}}$ on the left hand side, this is because we can express $\boldsymbol{F_{BC}}$ in terms of $\boldsymbol{\ddot{p}_{sys}}$ from (1), a second derivative of positional state

$$ \boldsymbol{F_{BC}} = m_B \boldsymbol{\ddot{p}_{sys}} - \boldsymbol{F_{GB}} - \boldsymbol{F_T} $$