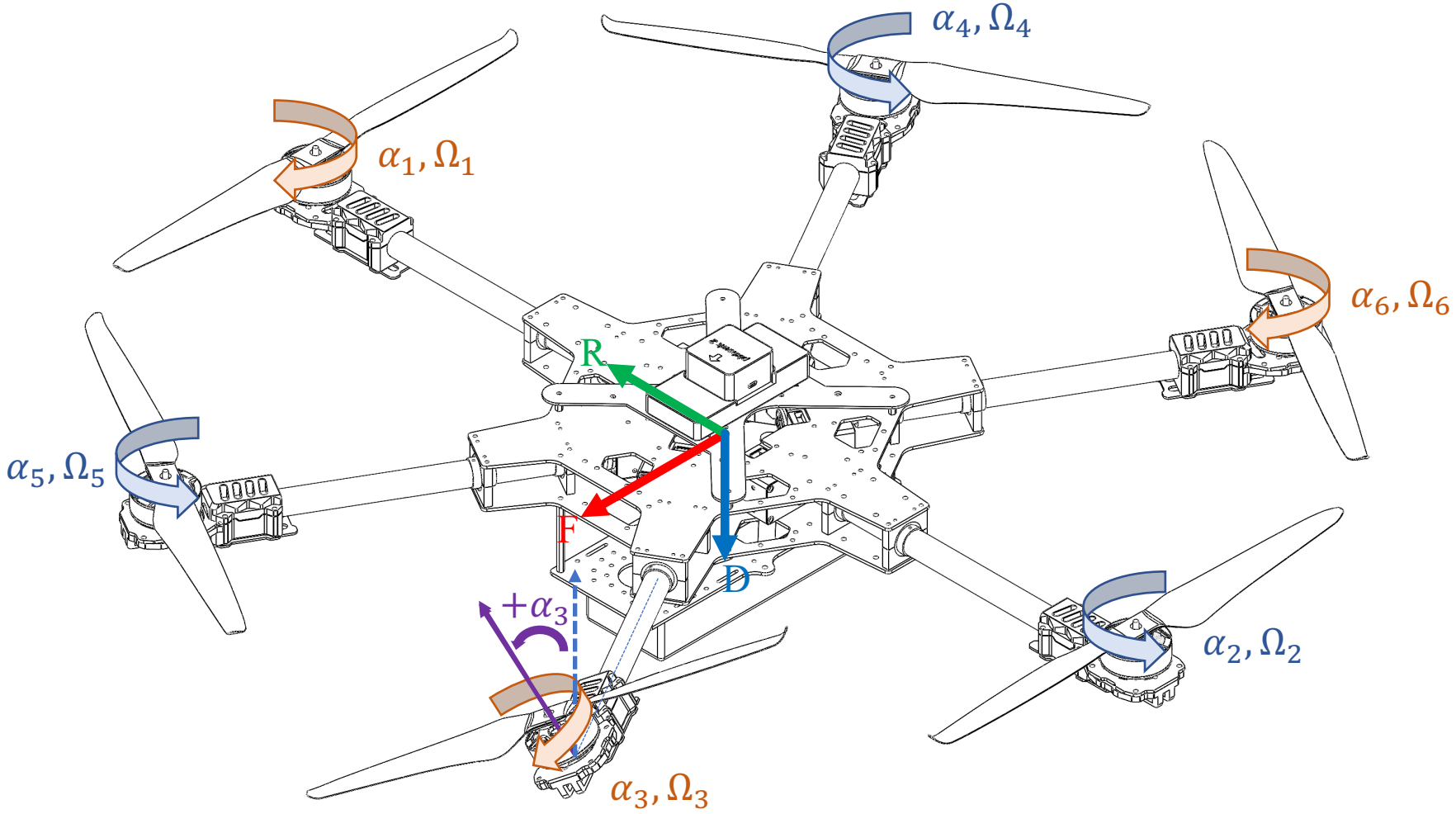
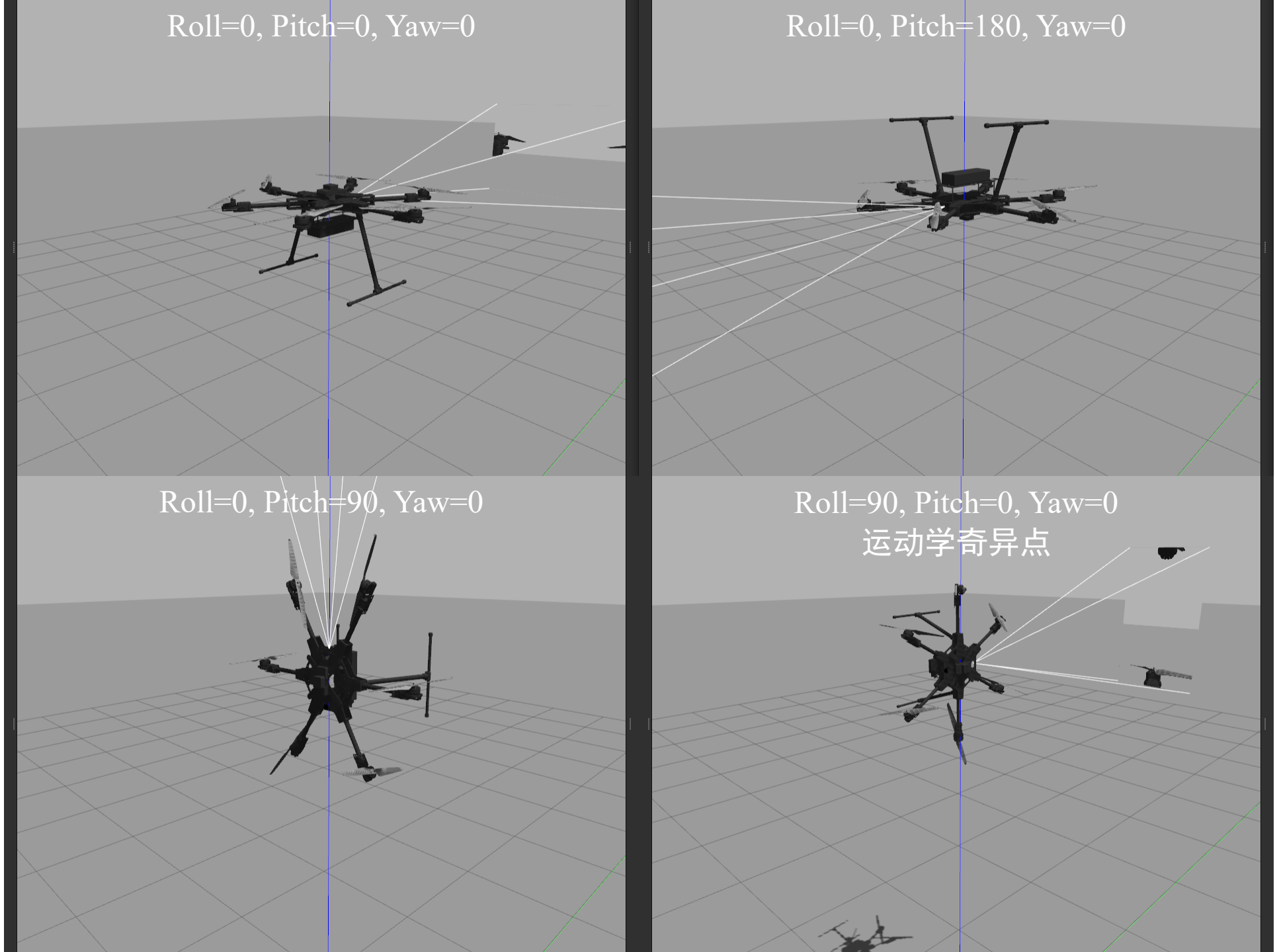
过驱动六旋翼无人机的自适应模型预测控制

Adaptice MPC for An Overactuated Hexacopter

答辩学生：刘越千 | 指导老师：陈浩耀教授



执行器能在机体坐标系下产生6DOF的合力和合力矩（wrench）
这种性质是“力和力矩的全向性”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Roll=0, Pitch=180, Yaw=0
Roll=0, Pitch=90, Yaw=0
Roll=90, Pitch=0, Yaw=0
运动学奇异点

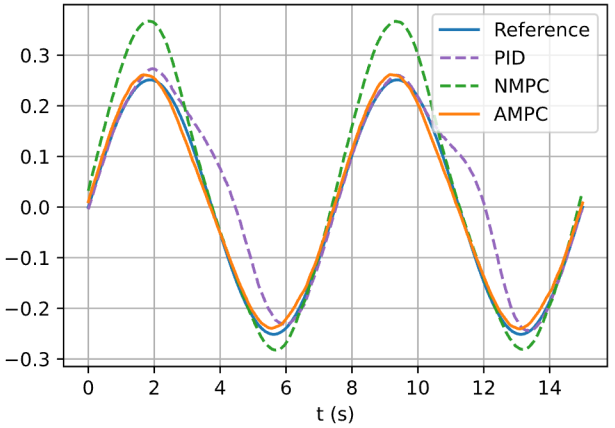
Pros:

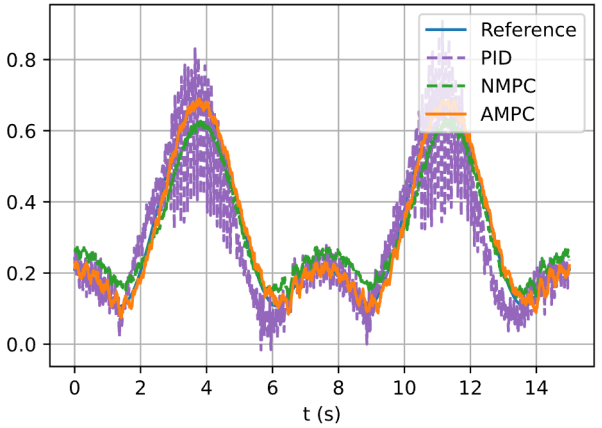
- 姿态与位置控制独立
- 与环境交互时更轻松

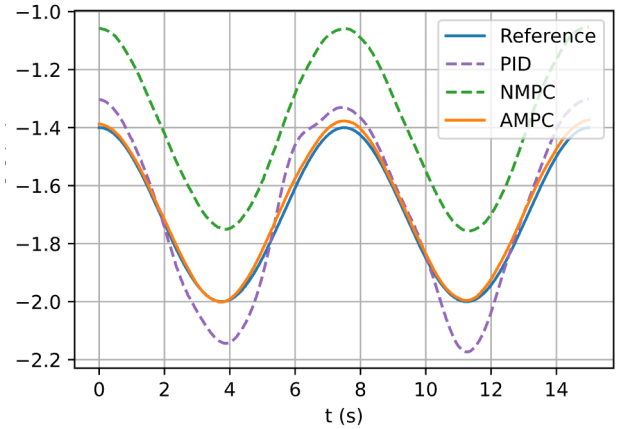
Cons:

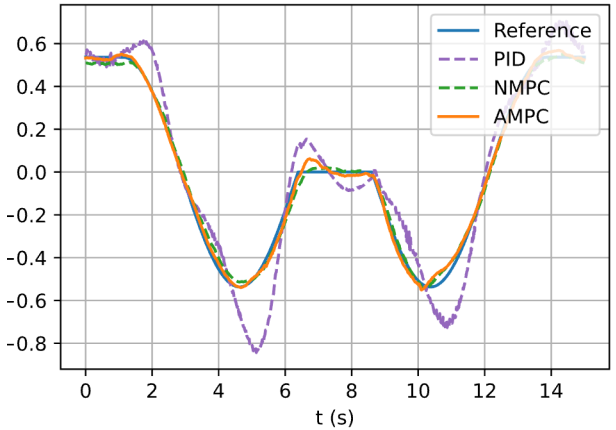
- 结构复杂
- 建模困难
- 时变的系统动态
- 机臂倾转的死区和误差

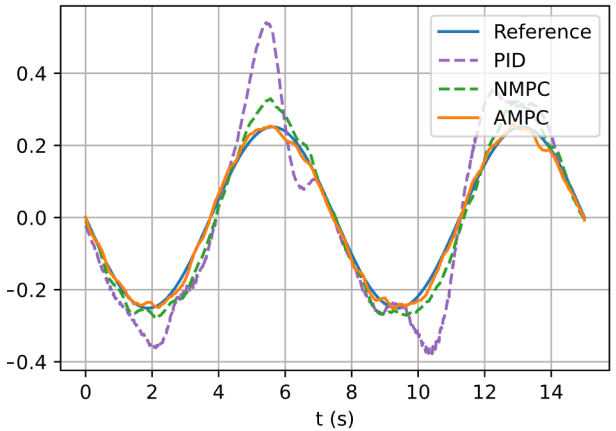
对控制算法的设计是较大的挑战











WHY 精确追踪轨迹？

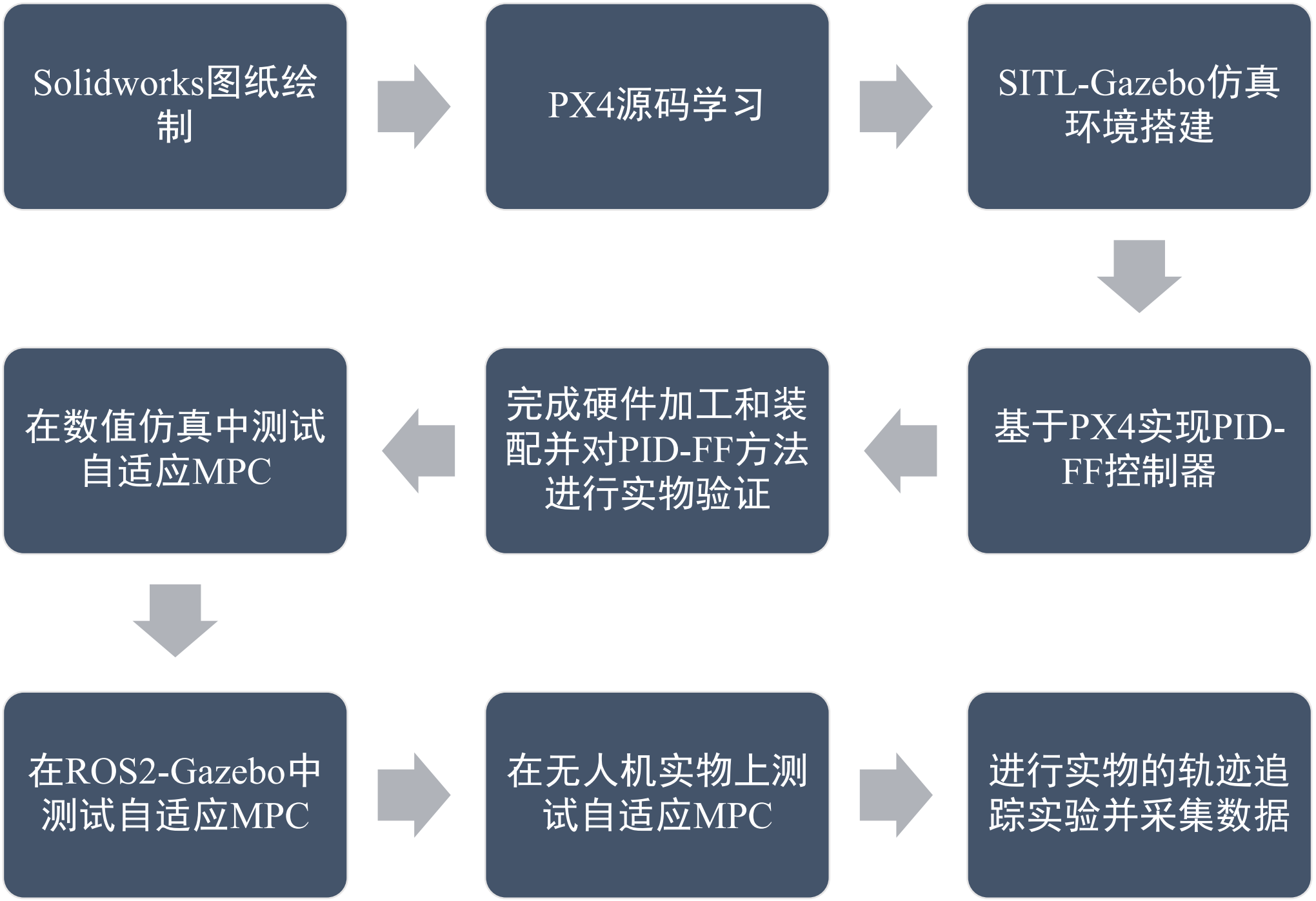
- 是衡量飞行器控制性能的重要指标
- 复杂环境下的自动飞行有精确追踪轨迹的要求

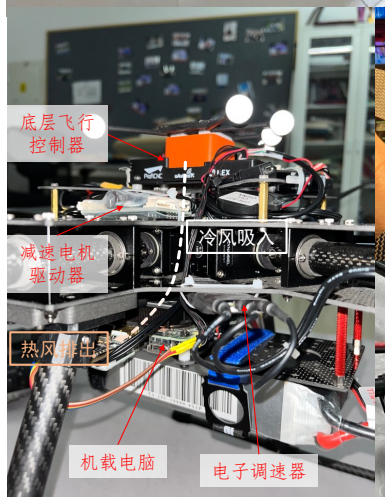
WHY MPC？

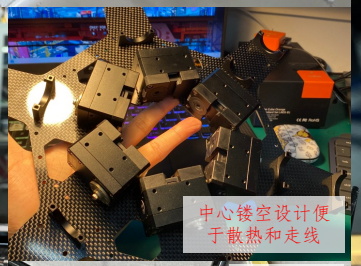
- PID和前馈控制的效果不好
- 可以在考虑约束的情况下对轨迹进行精确的追踪

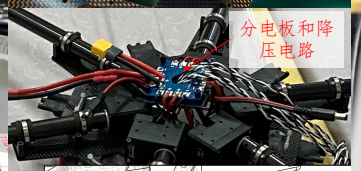
WHY 自适应？

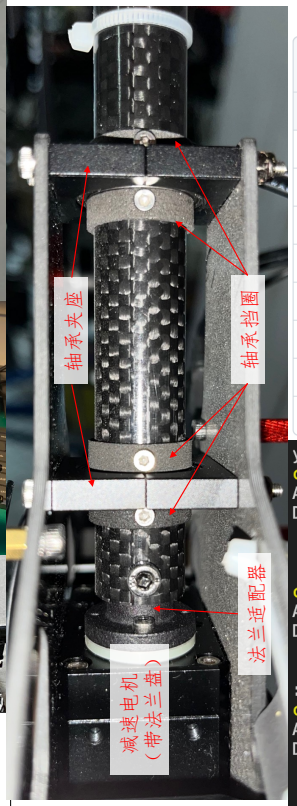
- MPC的性能受模型误差影响大
- 自适应能够极大减小MPC受模型误差的影响

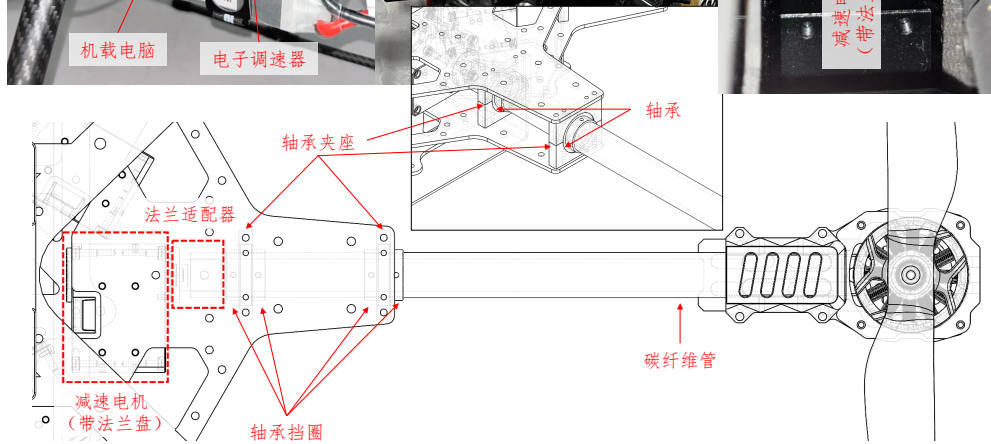

Solidworks图纸绘制
PX4源码学习
SITL-Gazebo仿真环境搭建
基于PX4实现PID-FF控制器
完成硬件加工和装配并对PID-FF方法进行实物验证
在数值仿真中测试自适应MPC
在ROS2-Gazebo中测试自适应MPC
在无人机实物上测试自适应MPC
进行实物的轨迹追踪实验并采集数据

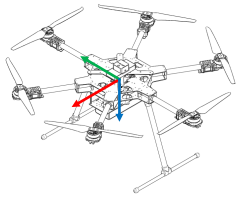


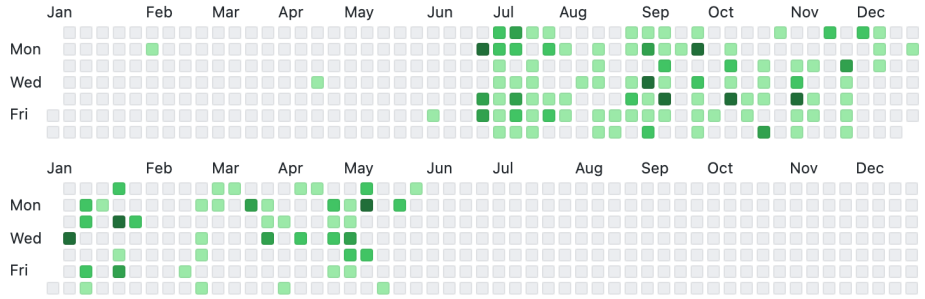












ErcBunny release 1.0 — `fc722c7` 2 days ago — **63** commits

PX4-Autopilot @ 140b956	fix bug: CA compute desired rotors speed	8 days ago
img	release 1.0	2 days ago
matlab-workspace	formulate ocp using acados	3 months ago
ros1-workspace/src	formulate ocp using acados	3 months ago
ros2-workspace/src	release 1.0	2 days ago
scripts	fix mpc dynamics issue, now gz sim is REALLY GOOD	10 days ago
.gitignore	backup gazebo sim results	23 days ago
.gitmodules	formulate ocp using acados	3 months ago
readme.md	release 1.0	2 days ago

```
yueqian@Yueqians-MacBook-Air omniHex % git log
commit f77ea038a9c0021a455c5f10f610ba942a00c946 (HEAD -> master, origin/master, origin/HEAD)
Author: Yueqian Liu <yueqianliu@outlook.com>
Date:   Sat May 21 21:36:26 2022 +0800

    fix mpc dynamics issue, now gz sim is REALLY GOOD

commit
Author:
Date:

    don
:...ski
commit                                                          /HEAD)
Author:
Date:

    fix

commit
Author:
Date:

    don

commit
Author:
Date:

    test stage0: done

commit 0d7498420111254ae15806f019cbe6565cf9e21d
Author: Yueqian Liu <yueqianliu@outlook.com>
Date:   Mon May 9 20:54:36 2022 +0800

    test stage0: offboard
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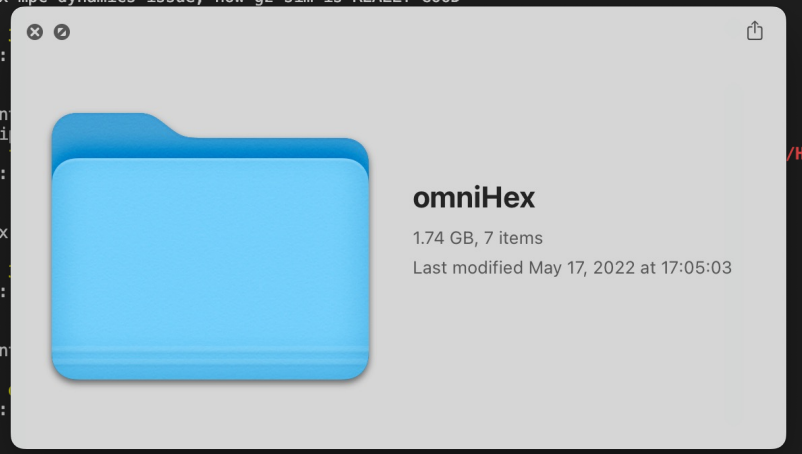
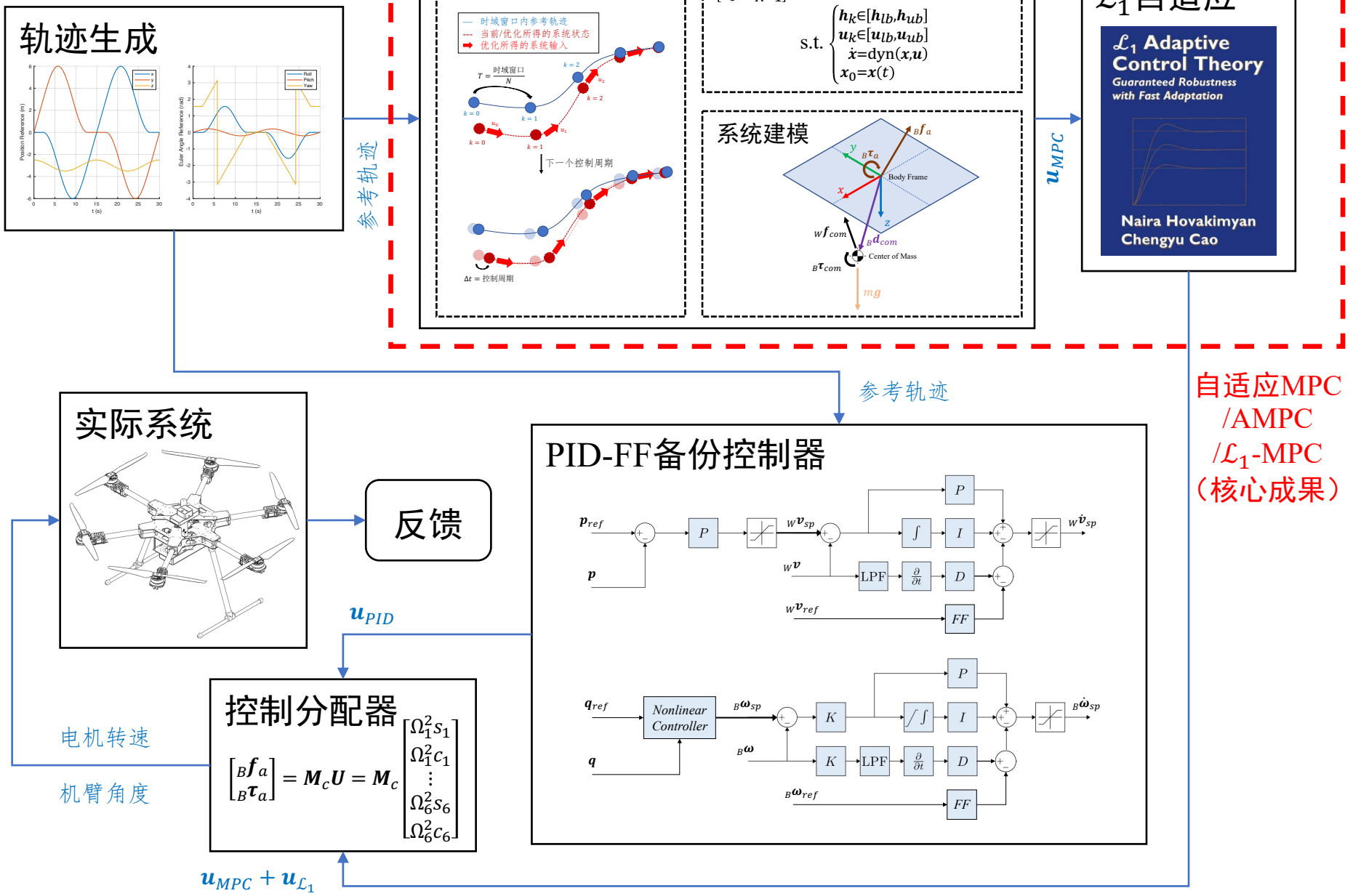
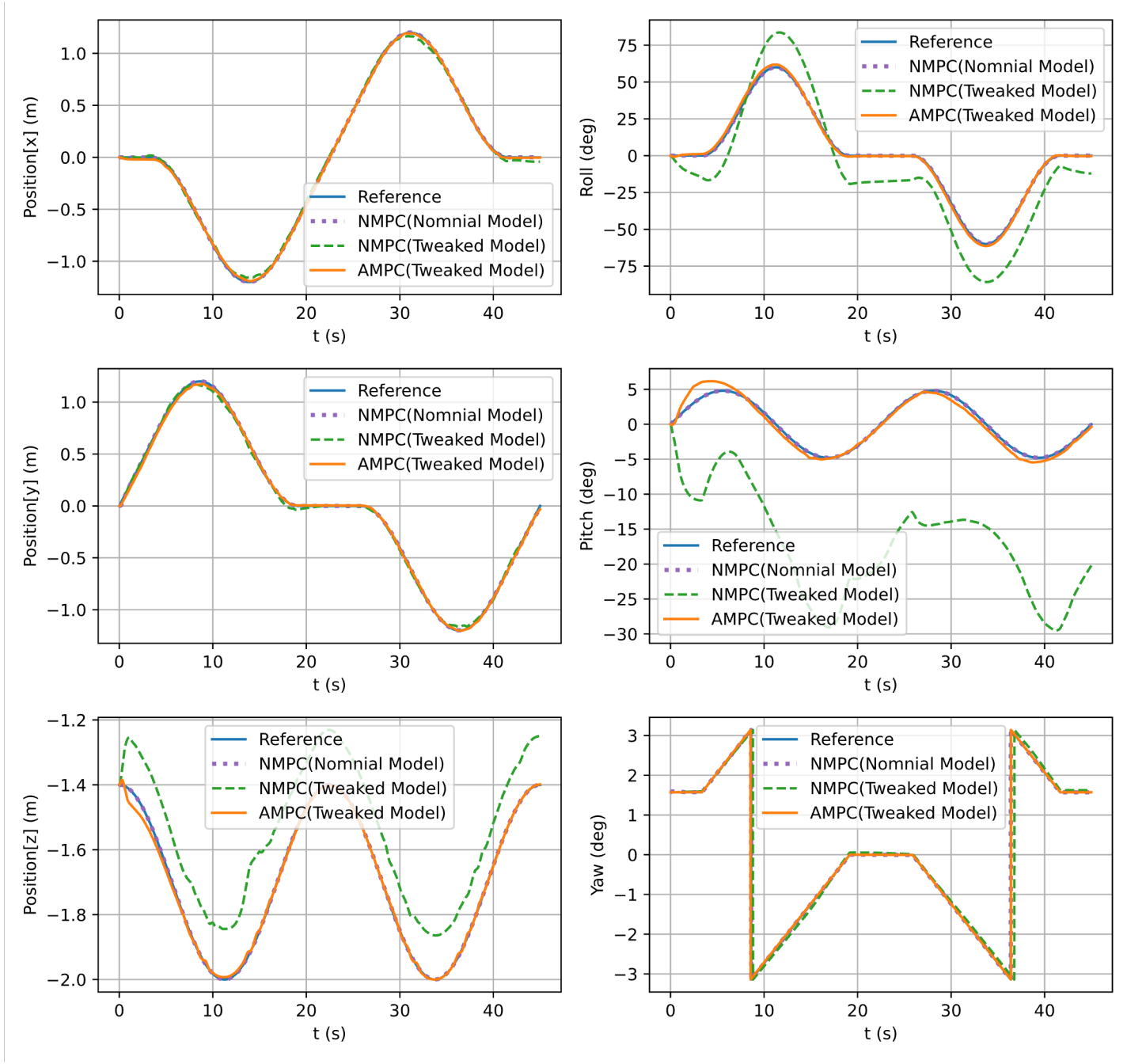
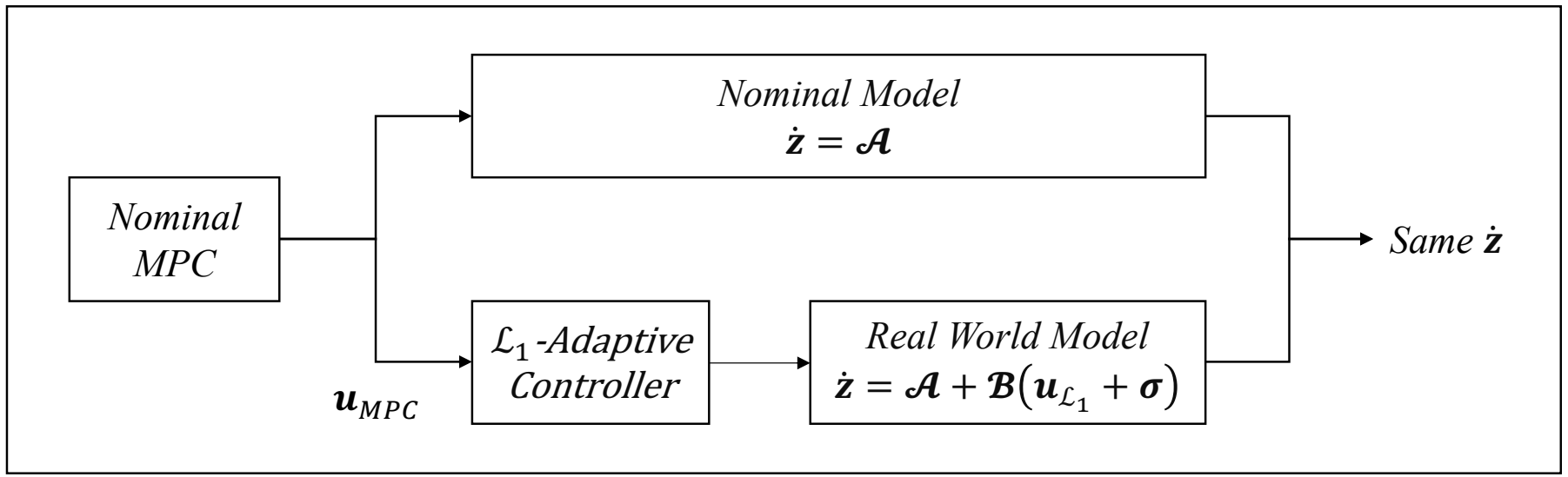


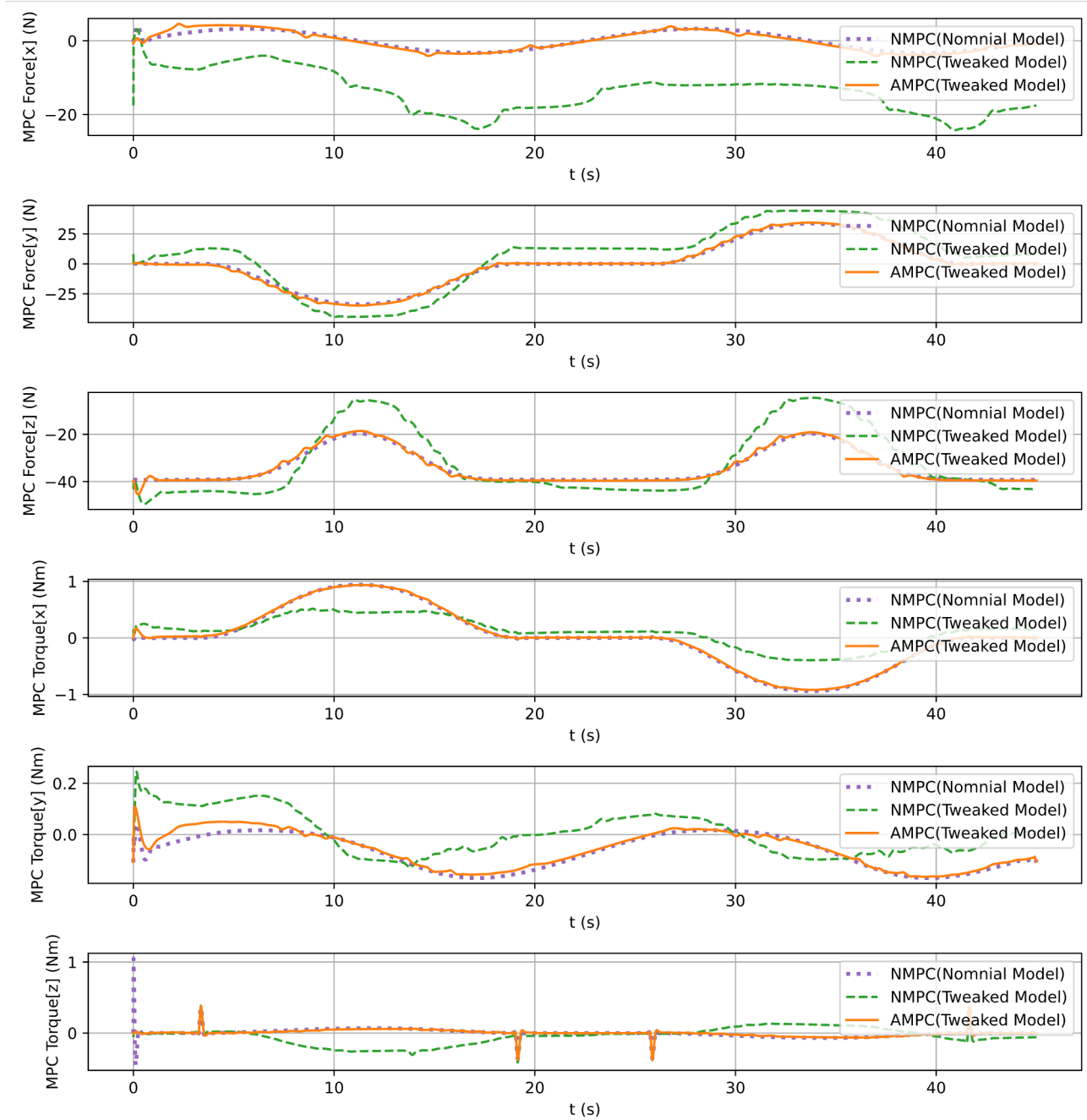

轨迹生成
参考轨迹
NMPC
滚动优化
时域窗口内参考轨迹
当前/优化所得的系统状态
优化所得的系统输入
下一个控制周期
Δt = 控制周期
最优控制问题
系统建模
Body Frame
Center of Mass
u_{MPC}
$\mathcal{L}_1$自适应
$\mathcal{L}_1$ Adaptive Control Theory
Guaranteed Robustness with Fast Adaptation
Naira Hovakimyan
Chengyu Cao
自适应MPC
/AMPC
/$\mathcal{L}_1$-MPC
（核心成果）
参考轨迹
实际系统
反馈
PID-FF备份控制器
u_{PID}
控制分配器
电机转速
机臂角度
$u_{MPC} + u_{\mathcal{L}_1}$

数值仿真——追踪效果对比

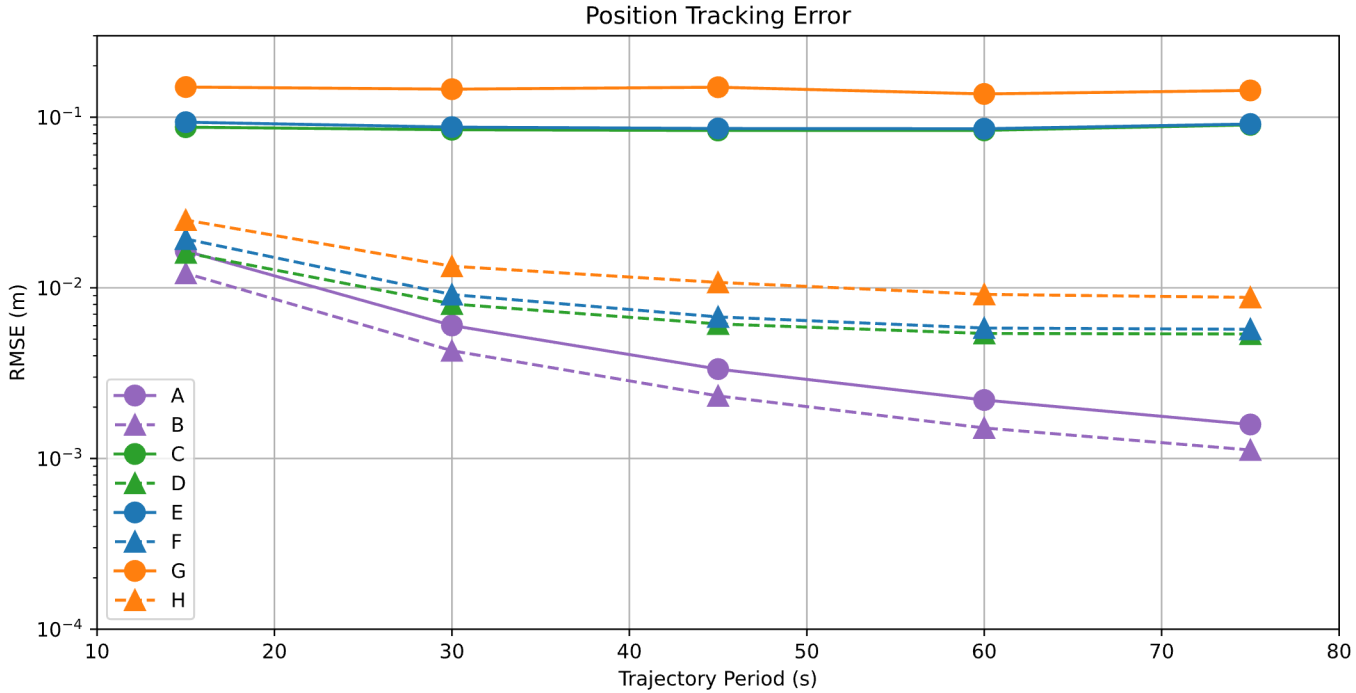

Position[x] (m)
Reference
NMPC(Nomnial Model)
NMPC(Tweaked Model)
AMPC(Tweaked Model)
t (s)
Roll (deg)
Position[y] (m)
Pitch (deg)
Position[z] (m)
Yaw (deg)

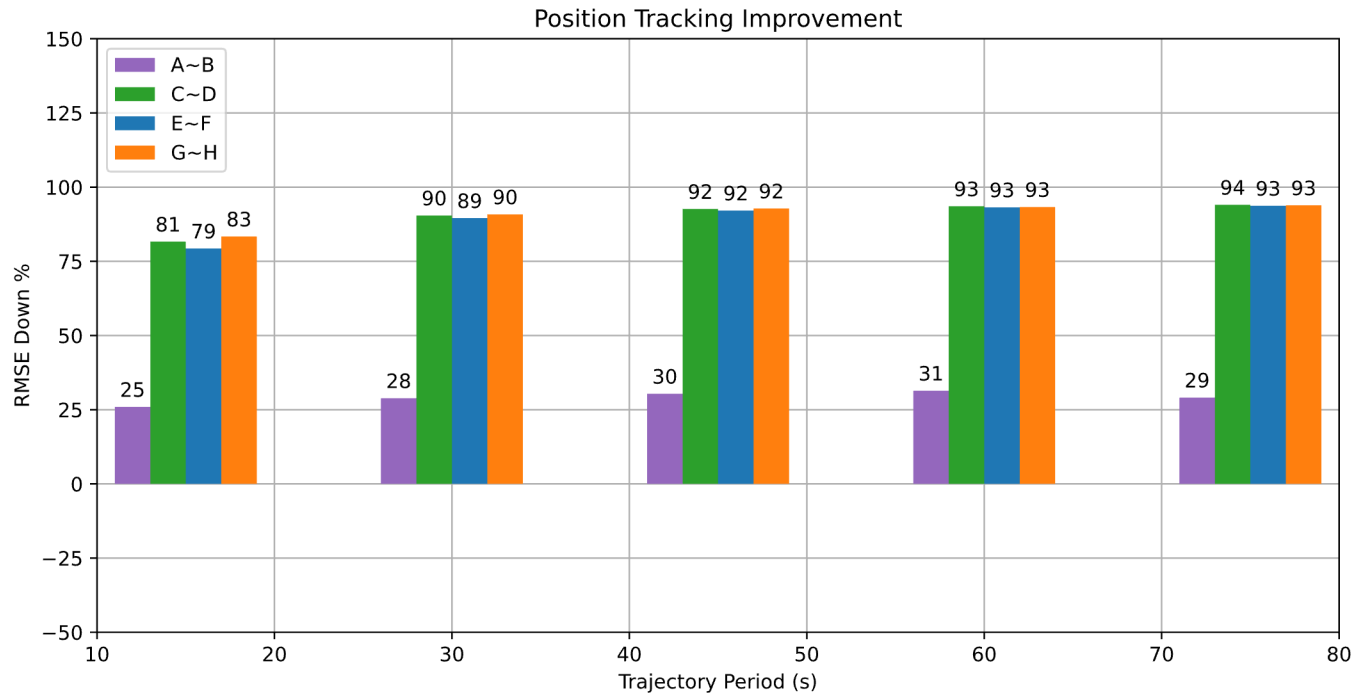

Nominal Model
$\dot{\boldsymbol{z}} = \boldsymbol{\mathcal{A}}$
Nominal MPC
$\mathcal{L}_1$-Adaptive Controller
Real World Model
$\dot{\boldsymbol{z}} = \boldsymbol{\mathcal{A}} + \boldsymbol{\mathcal{B}}\left(\boldsymbol{u}_{\mathcal{L}_1} + \boldsymbol{\sigma}\right)$
Same $\dot{\boldsymbol{z}}$
$\boldsymbol{u}_{MPC}$

数值仿真——上层控制器输出

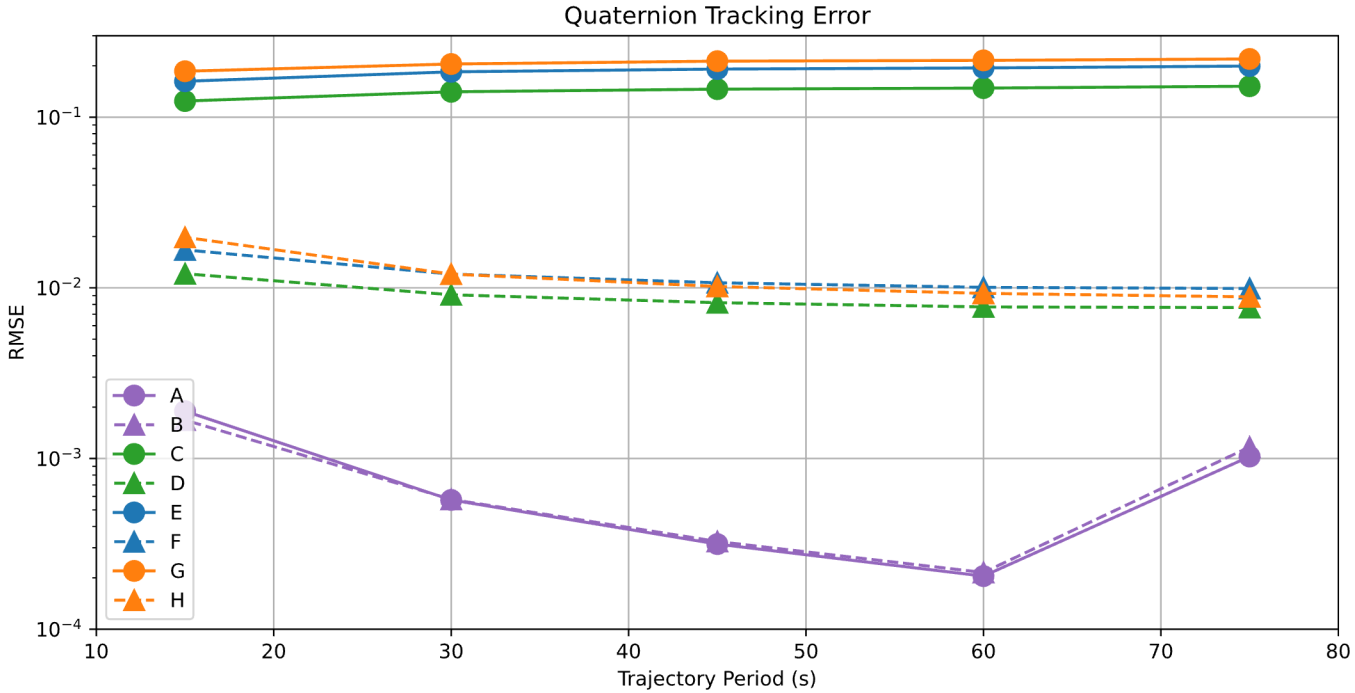


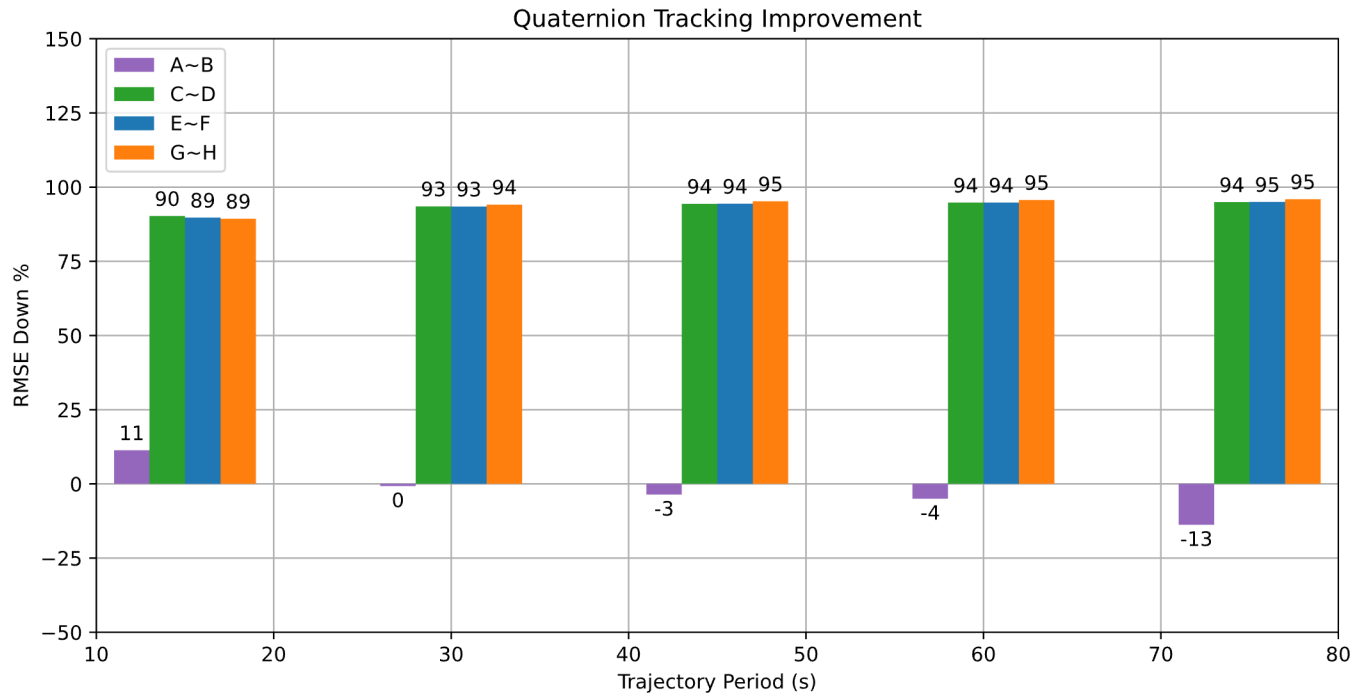
数值仿真——位置误差对比


Position Tracking Error
RMSE (m)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
A
B
C
D
E
F
G
H
10
20
30
40
50
60
70
80
Trajectory Period (s)

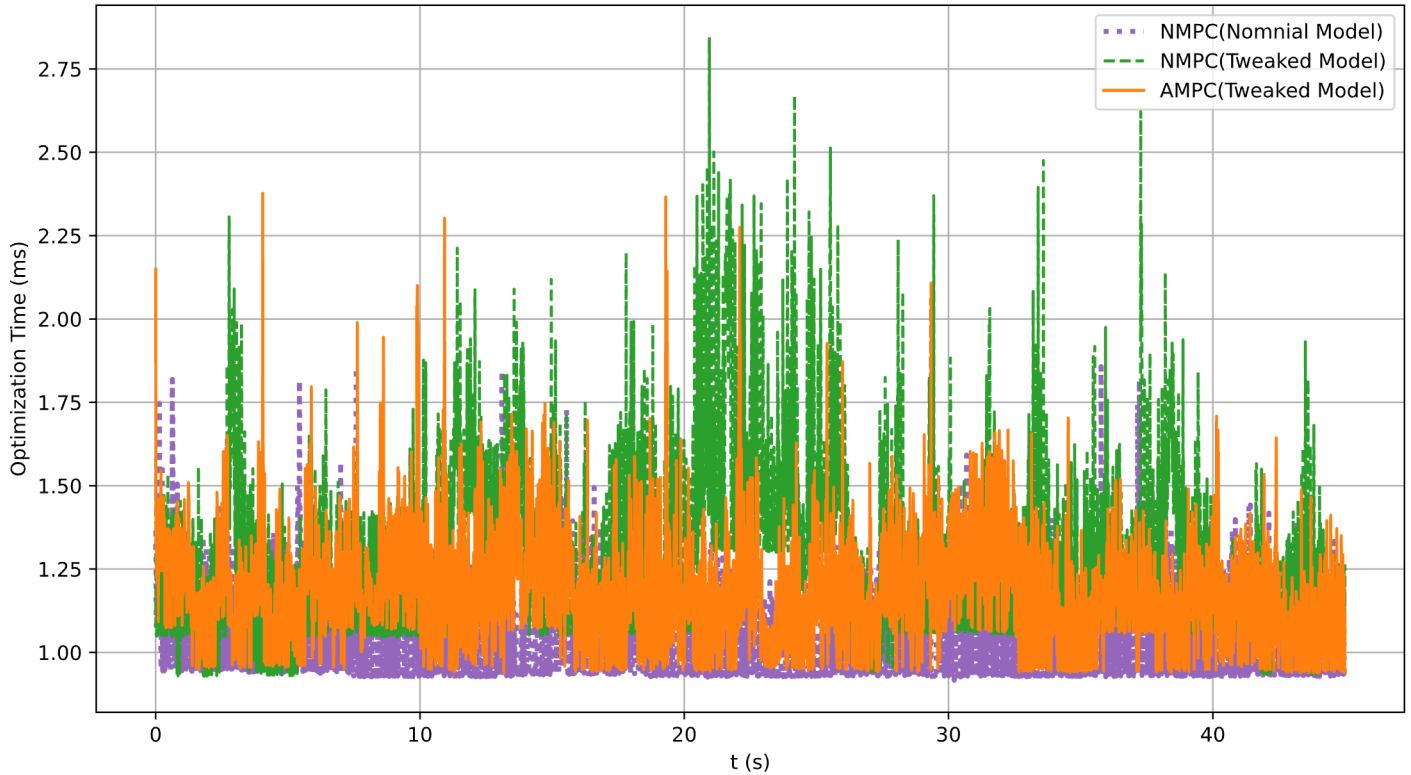

Position Tracking Improvement
RMSE Down %
150
125
100
75
50
25
0
−25
−50
A~B
C~D
E~F
G~H
25
81
79
83
28
90
89
90
30
92
92
92
31
93
93
93
29
94
93
93
10
20
30
40
50
60
70
80
Trajectory Period (s)

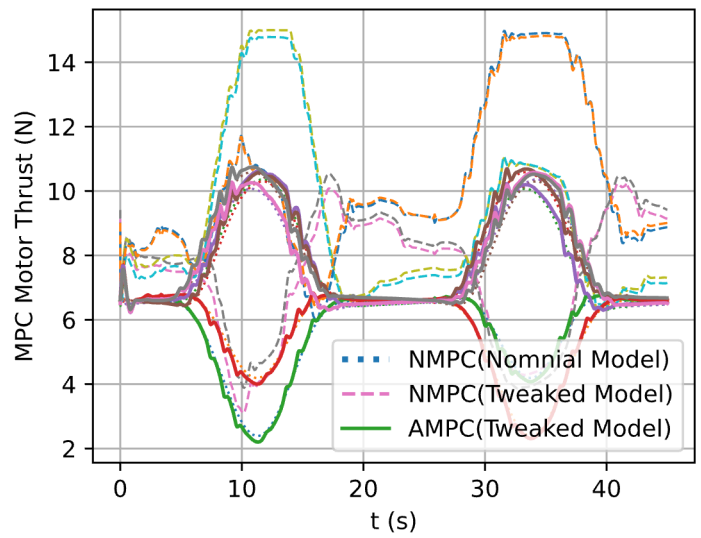
数值仿真——姿态误差对比

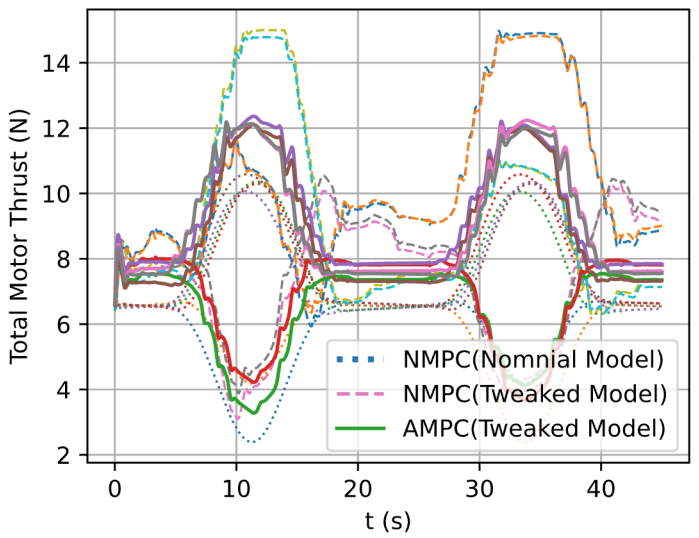

Quaternion Tracking Error
RMSE
10^{-1}
10^{-2}
10^{-3}
10^{-4}
A
B
C
D
E
F
G
H
10
20
30
40
50
60
70
80
Trajectory Period (s)


Quaternion Tracking Improvement
RMSE Down %
150
125
100
75
50
25
0
−25
−50
A~B
C~D
E~F
G~H
11
90 89 89
0
93 93 94
-3
94 94 95
-4
94 94 95
-13
94 95 95
10
20
30
40
50
60
70
80
Trajectory Period (s)

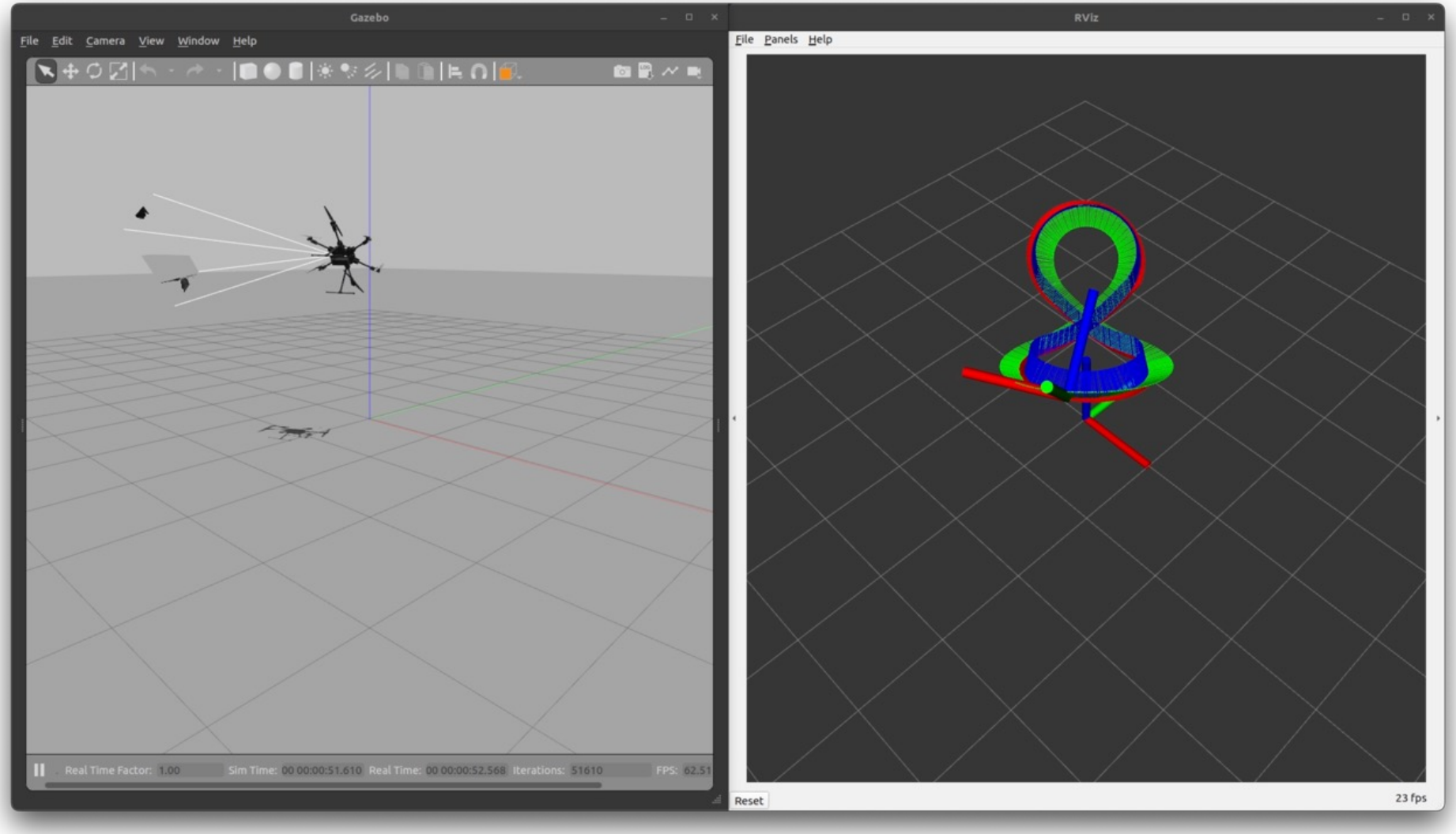
数值仿真——优化用时和总力和力矩





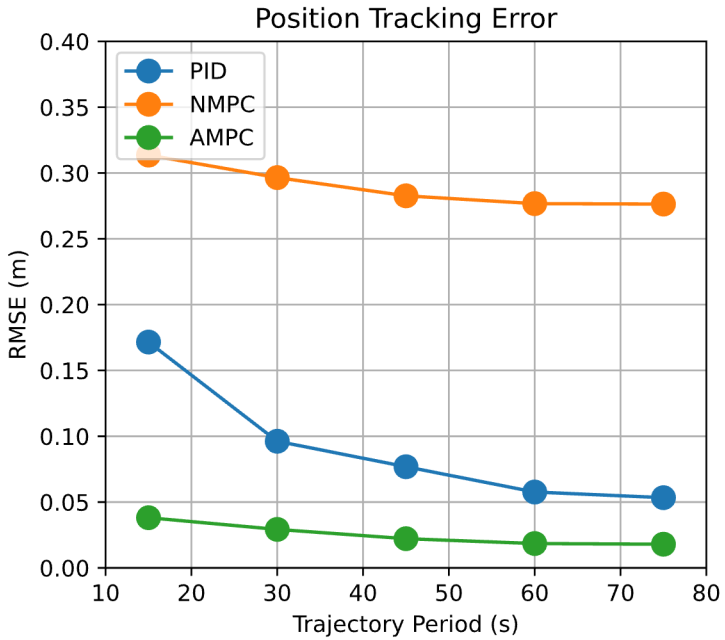


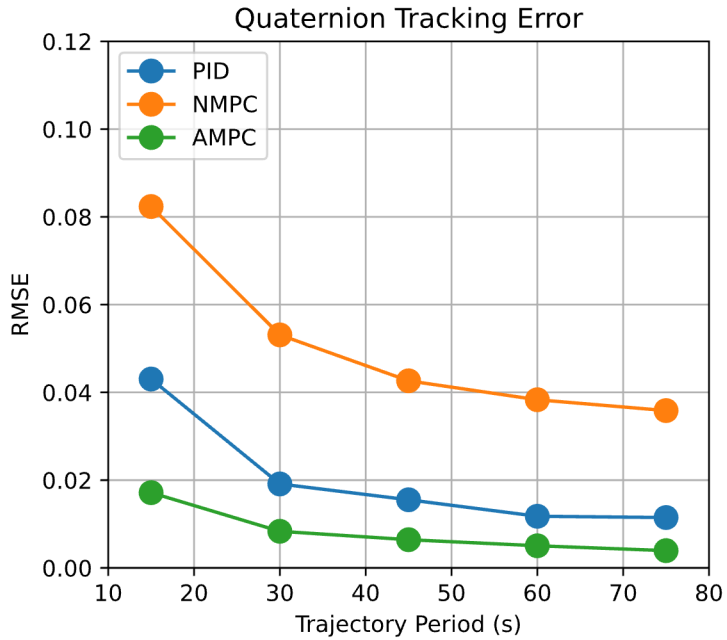
第三部分：Gazebo仿真丨环境示意图

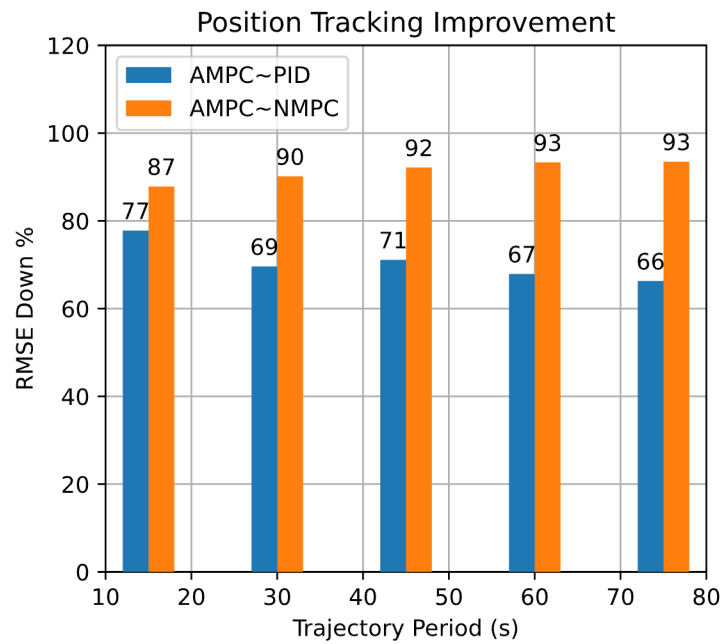


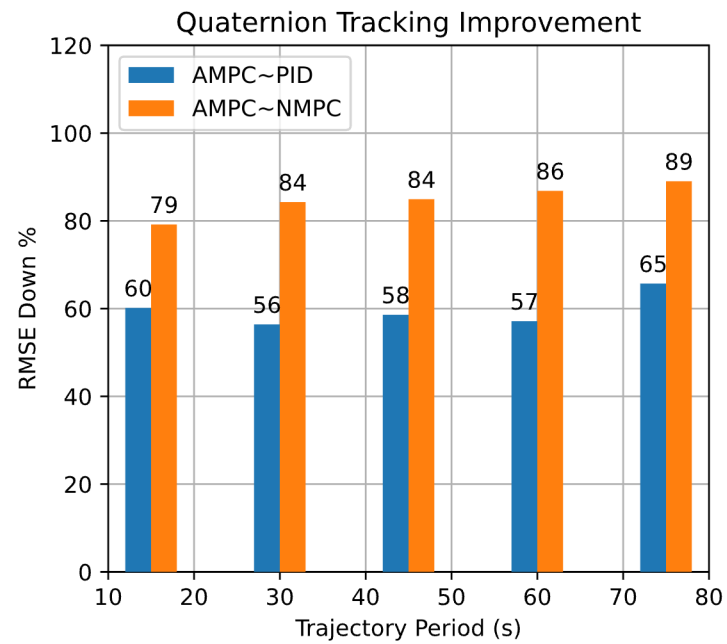
视频材料Available

Gazebo仿真 | 追踪误差对比

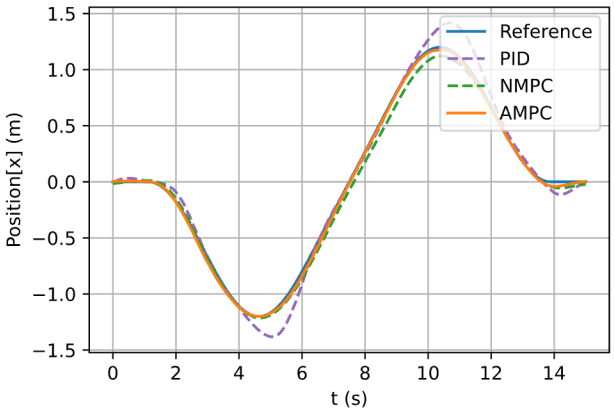


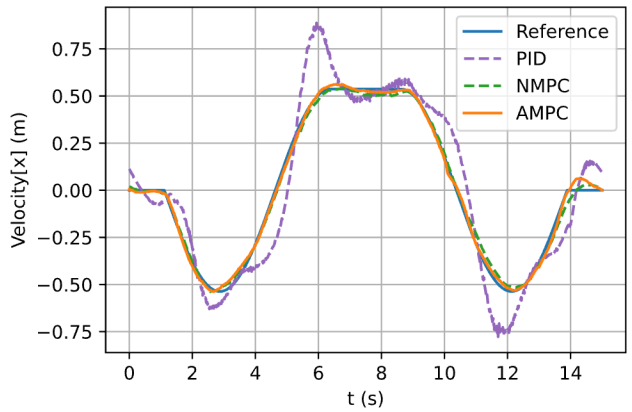


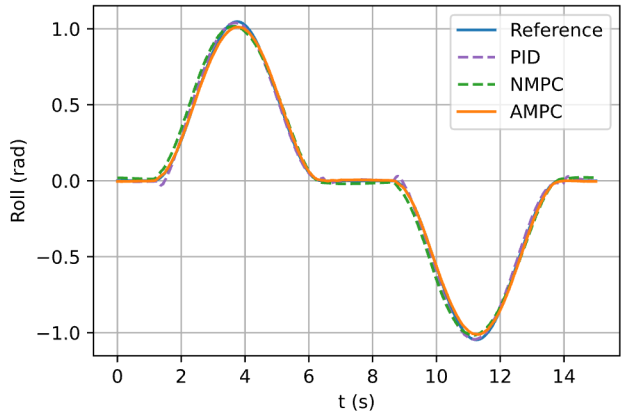


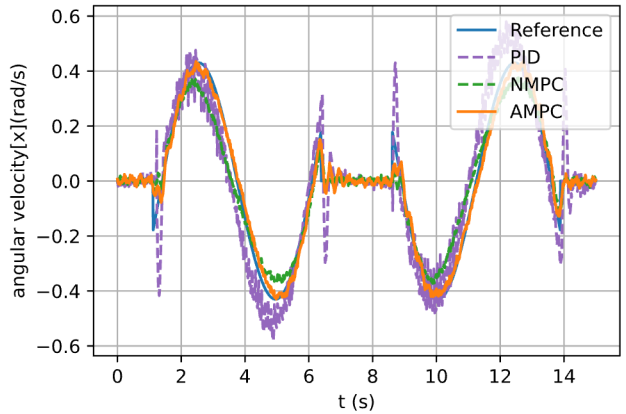


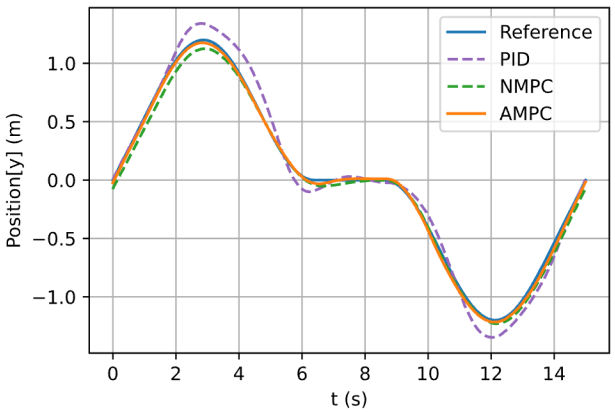
Gazebo仿真丨时域数据

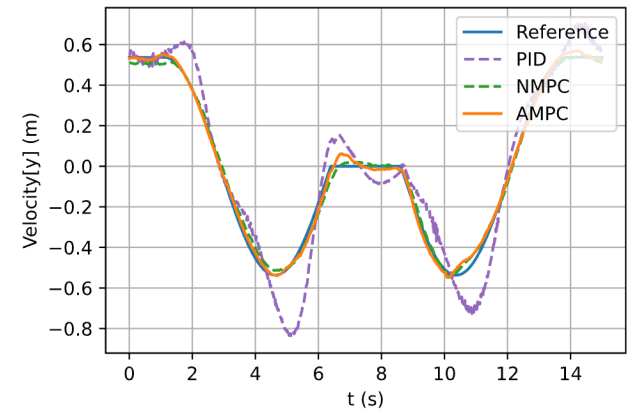


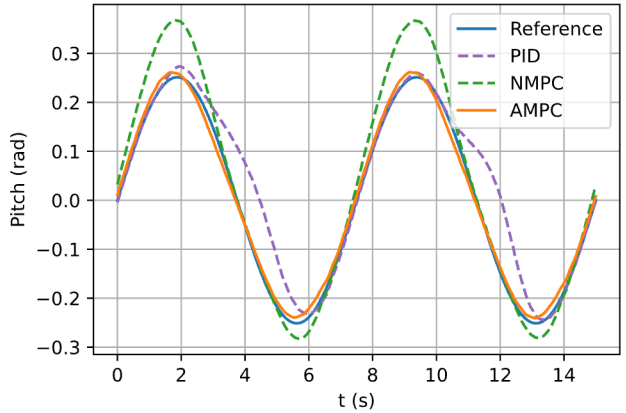


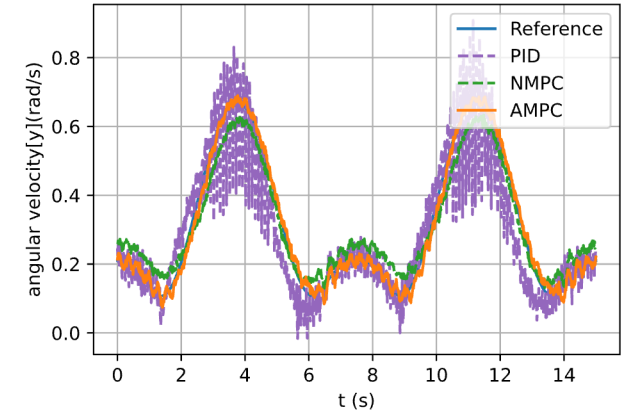


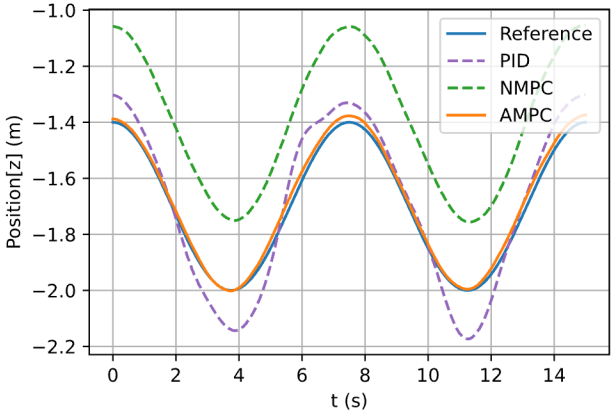


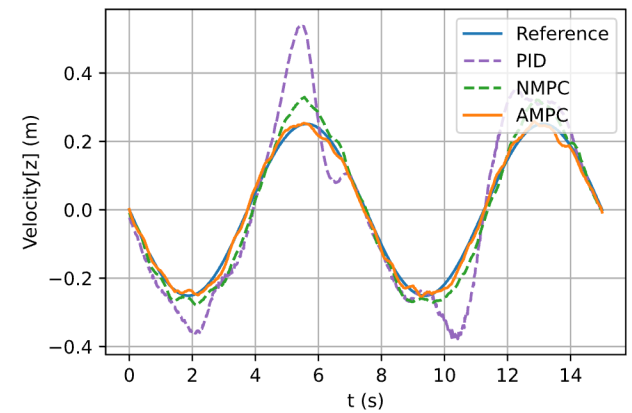


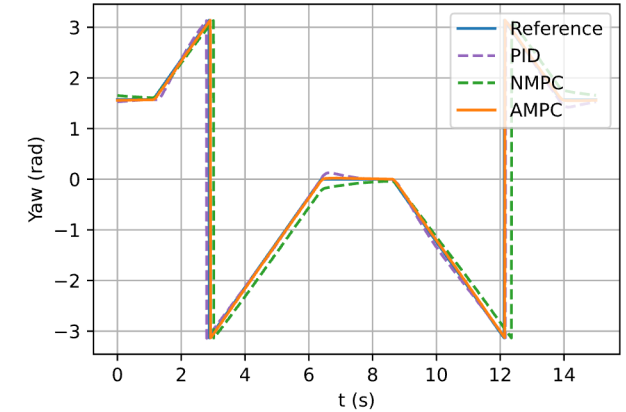


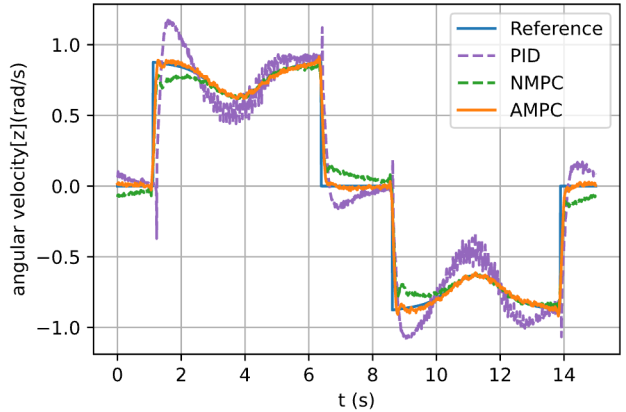




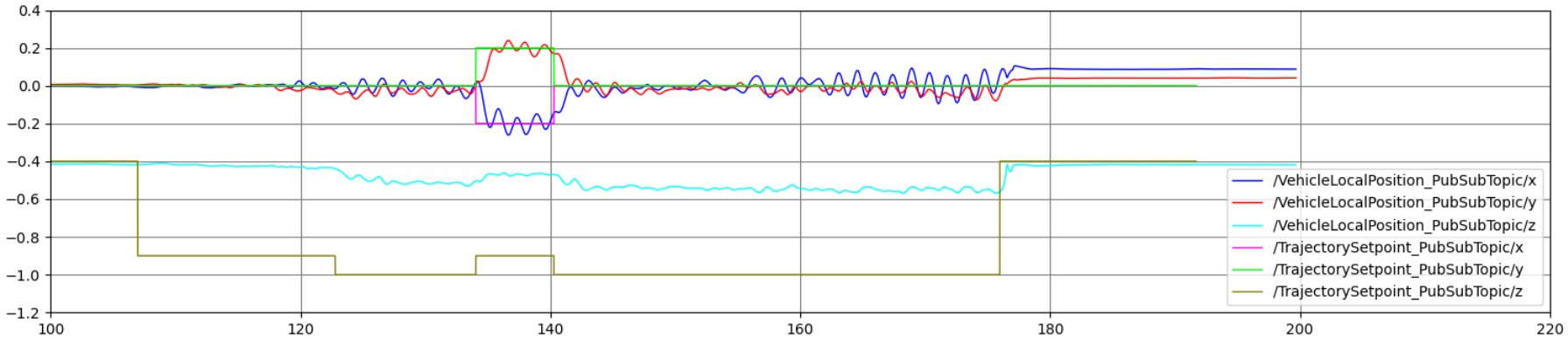


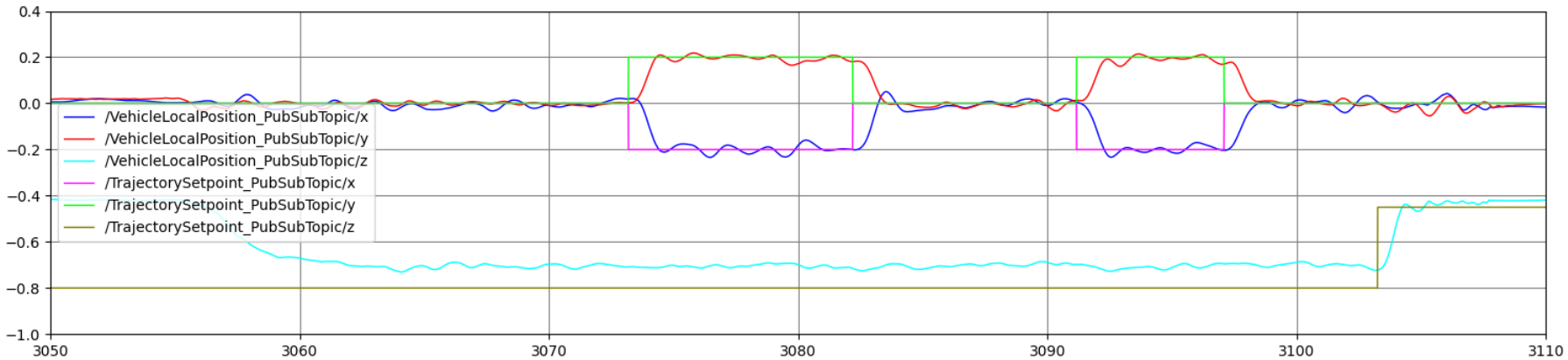




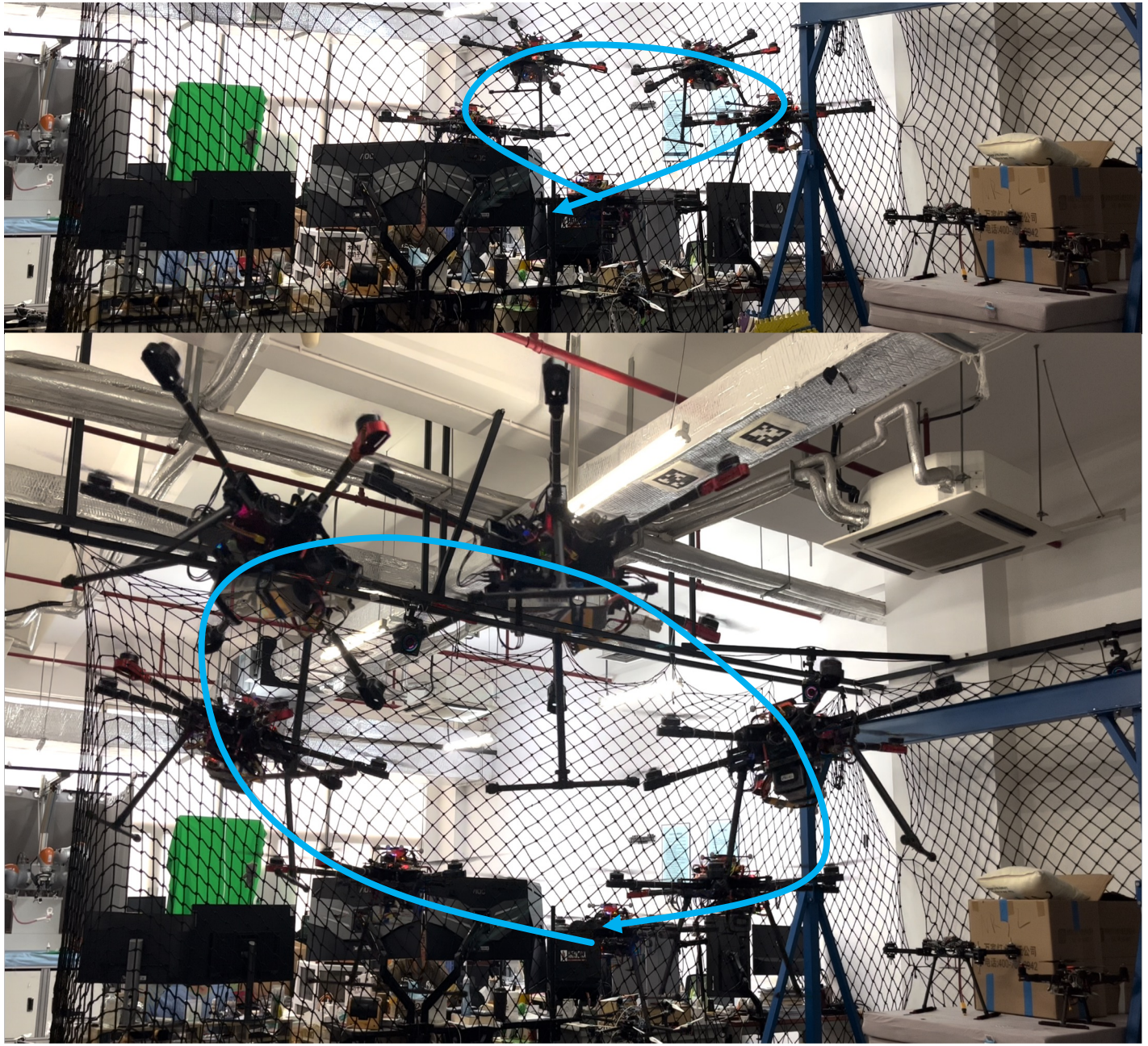


实物验证丨自适应算法的基本验证



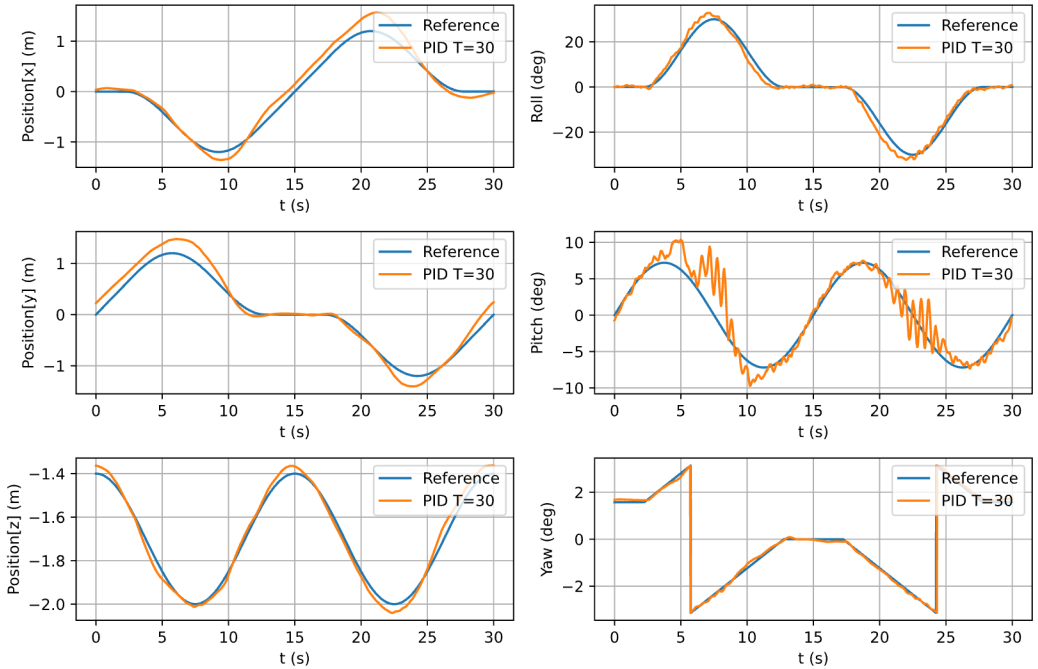


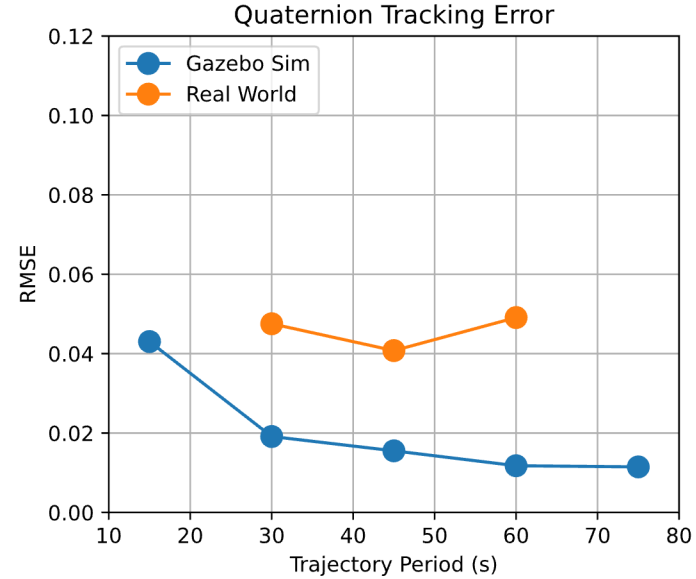
实物验证 | PID-FF实现基本轨迹跟踪

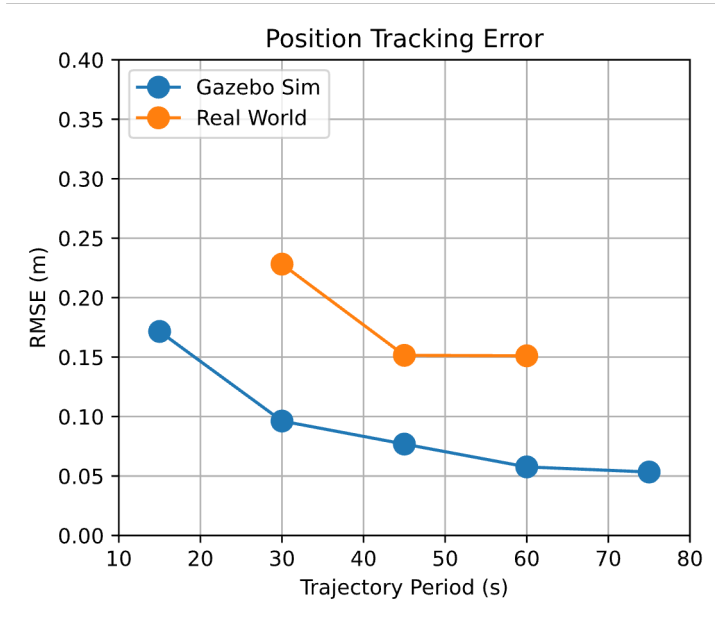


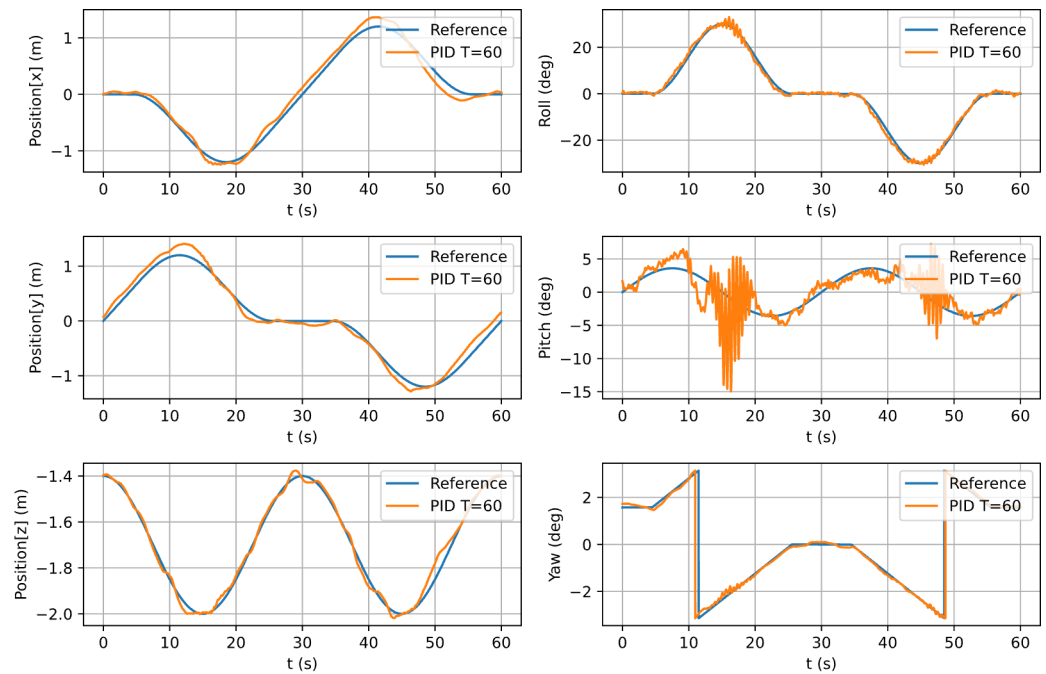
视频材料Available

实物验证 | PID-FF实现基本轨迹跟踪

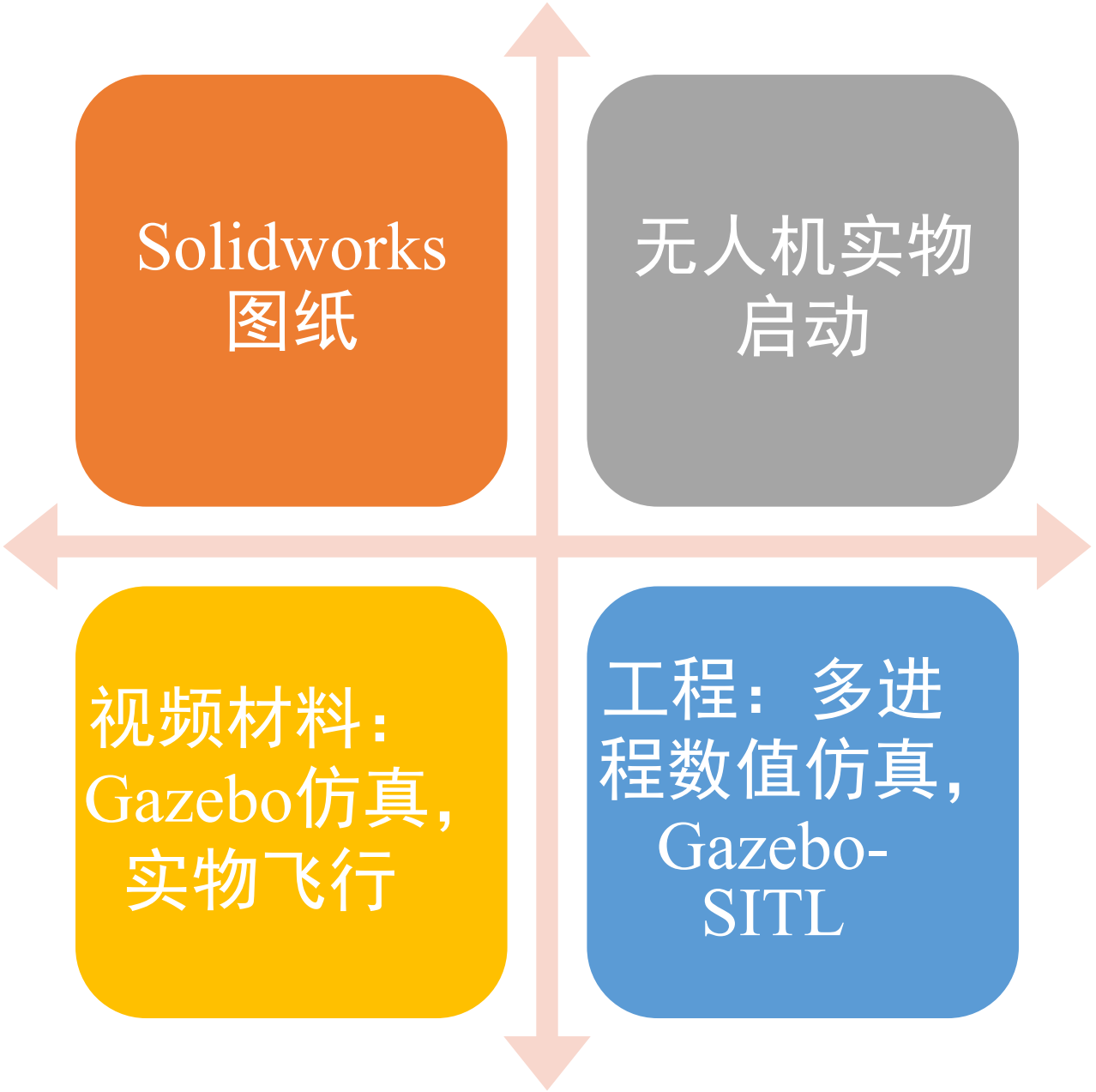






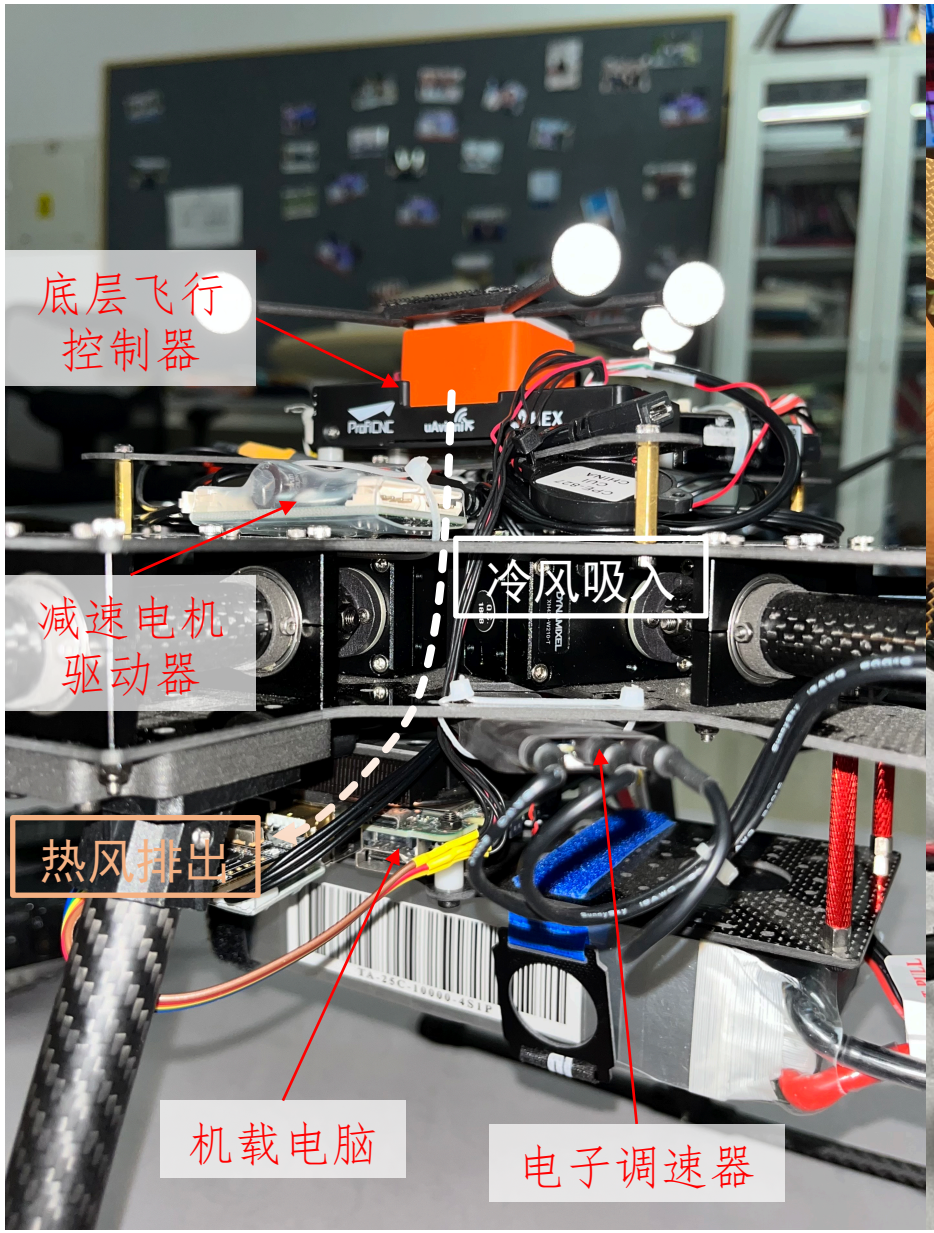


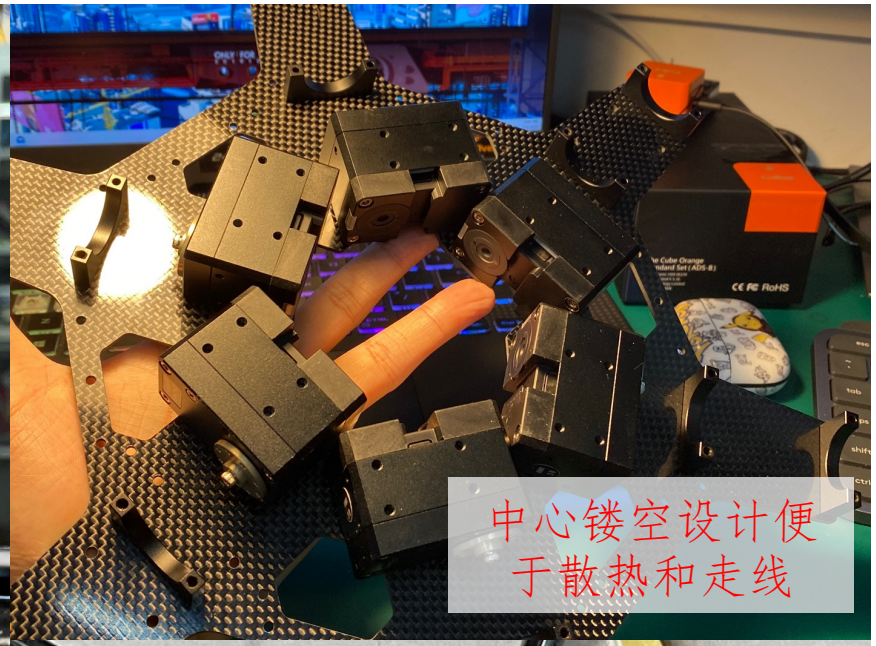
灵活展示

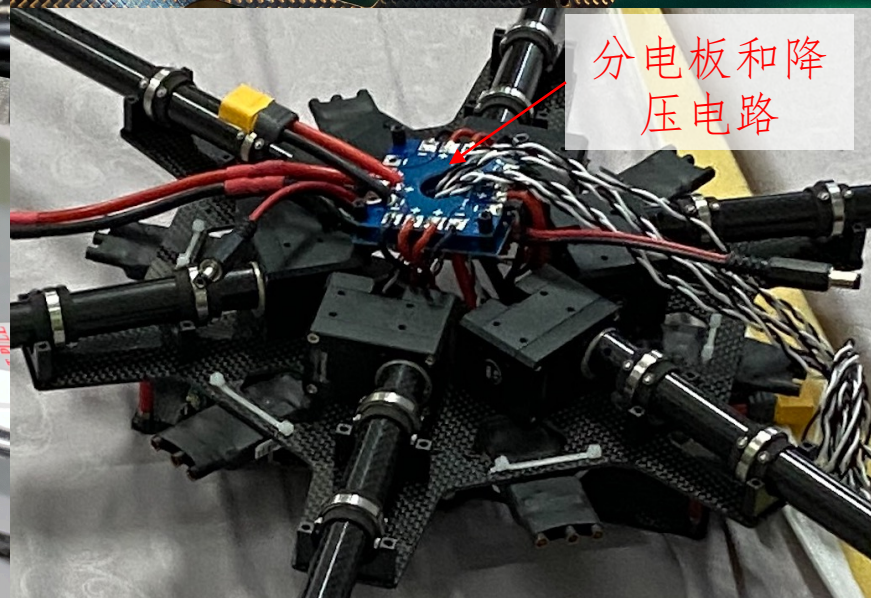

Solidworks
图纸
无人机实物
启动
视频材料：
Gazebo仿真，
实物飞行
工程：多进
程数值仿真，
Gazebo-
SITL

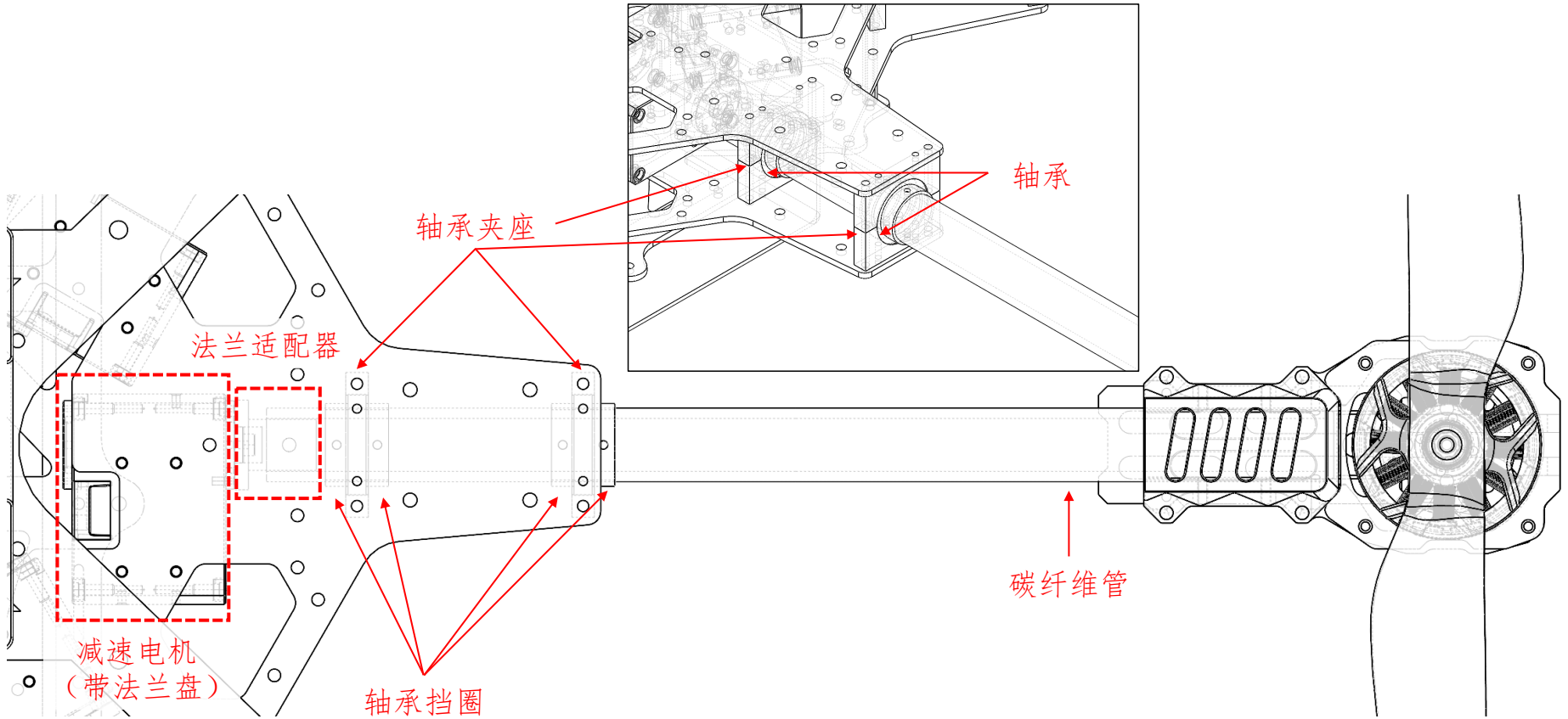
这里是华丽的分割线（页）
底下是Detailed Version

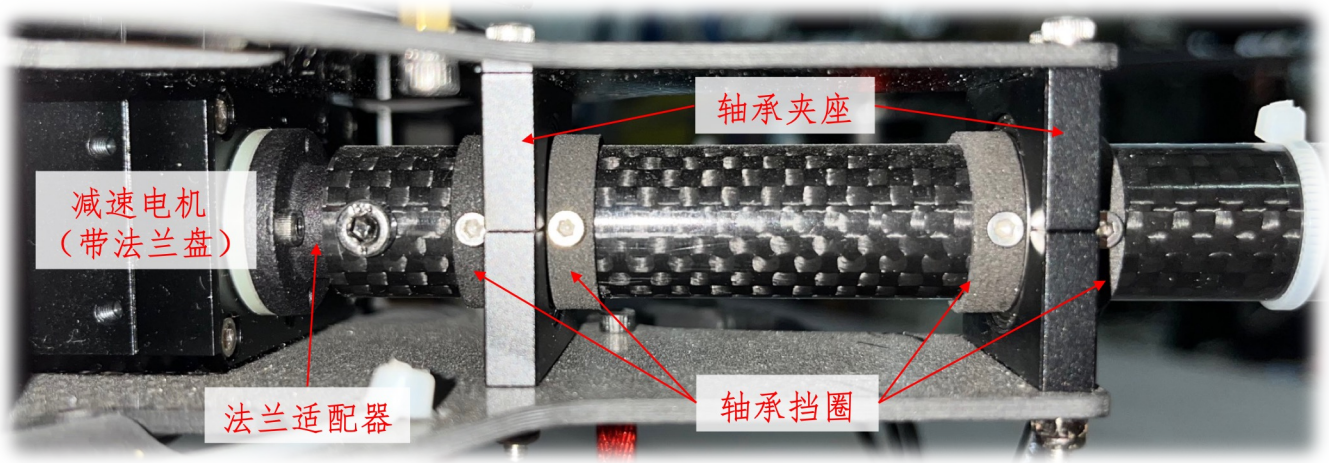
第一部分：硬件搭建 | 整体外观

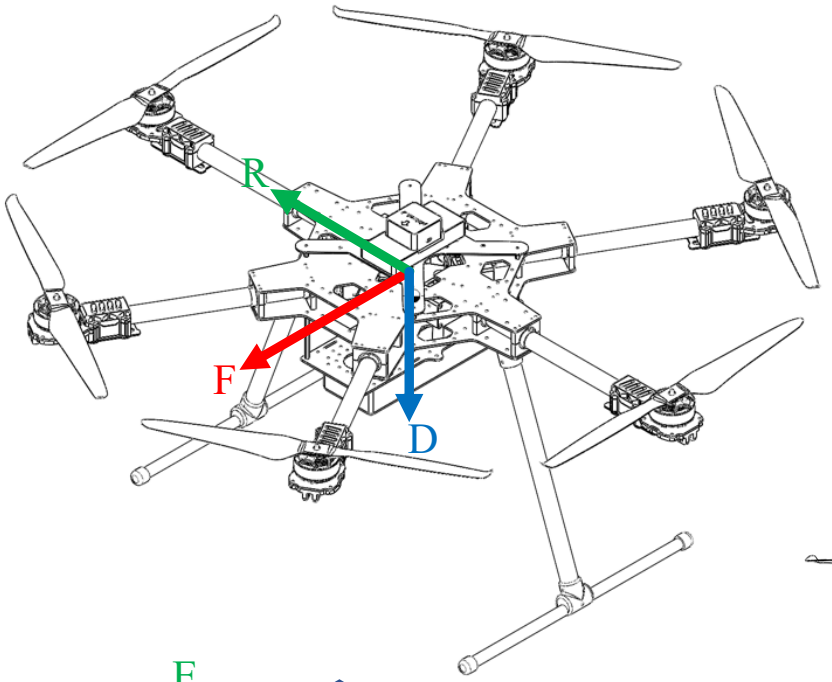

底层飞行
控制器
减速电机
驱动器
冷风吸入
热风排出
机载电脑
电子调速器

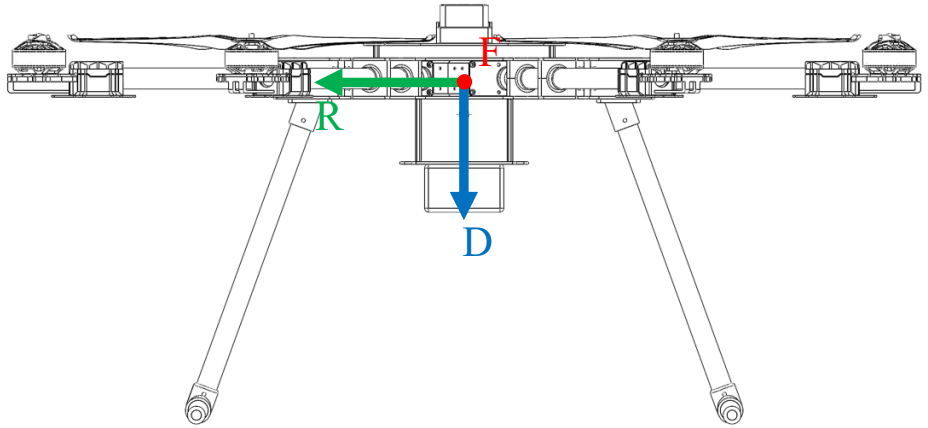

中心镂空设计便
于散热和走线

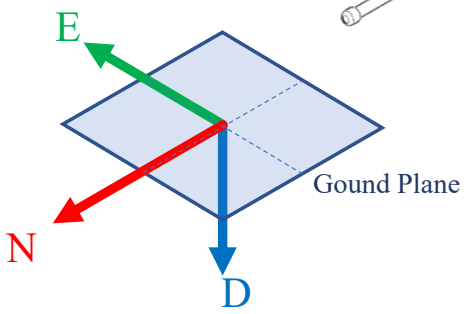

分电板和降
压电路

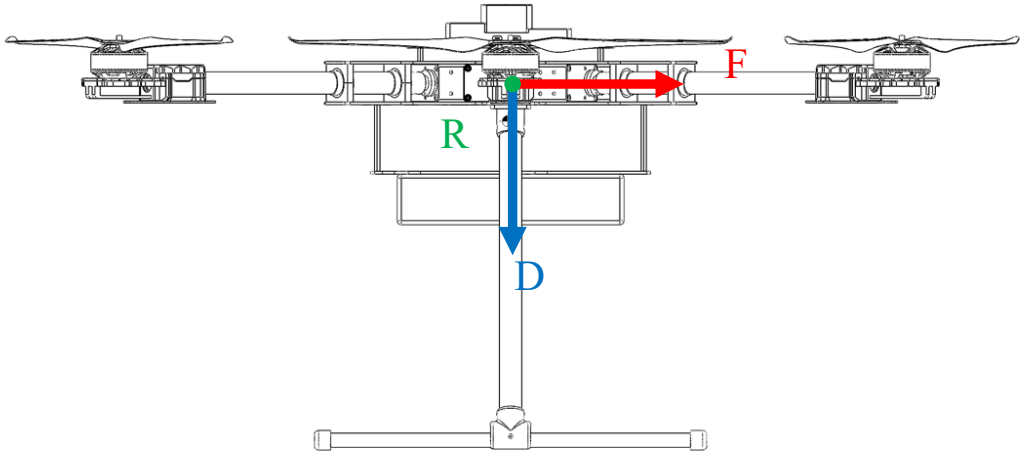

轴承
轴承夹座
法兰适配器
减速电机
（带法兰盘）
轴承挡圈
碳纤维管

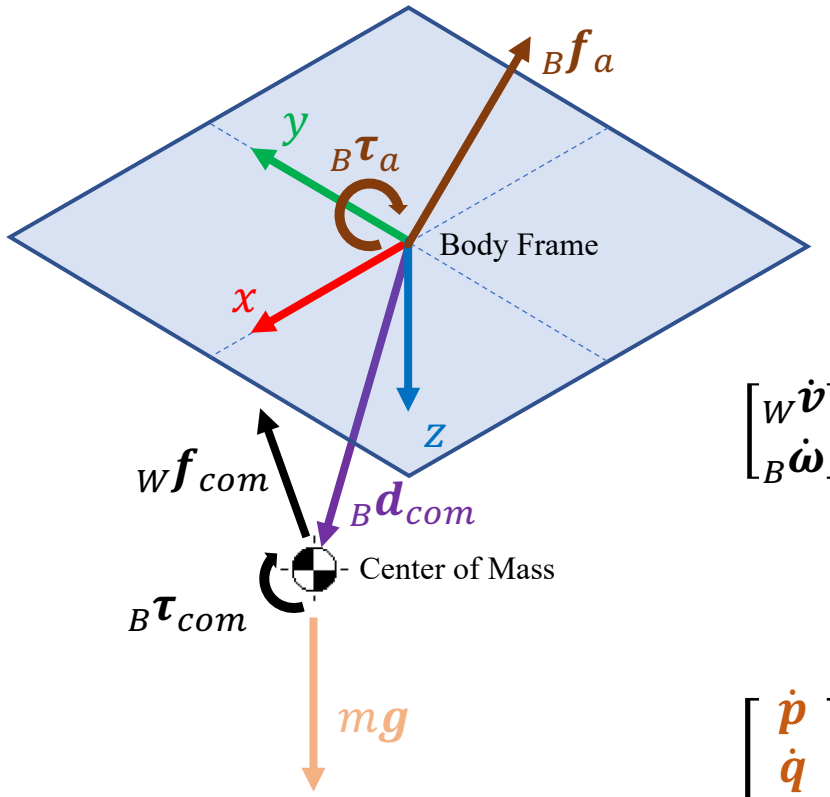

轴承夹座
减速电机
（带法兰盘）
法兰适配器
轴承挡圈


R
F
D


F
R
D


E
N
D
Gound Plane


F
R
D

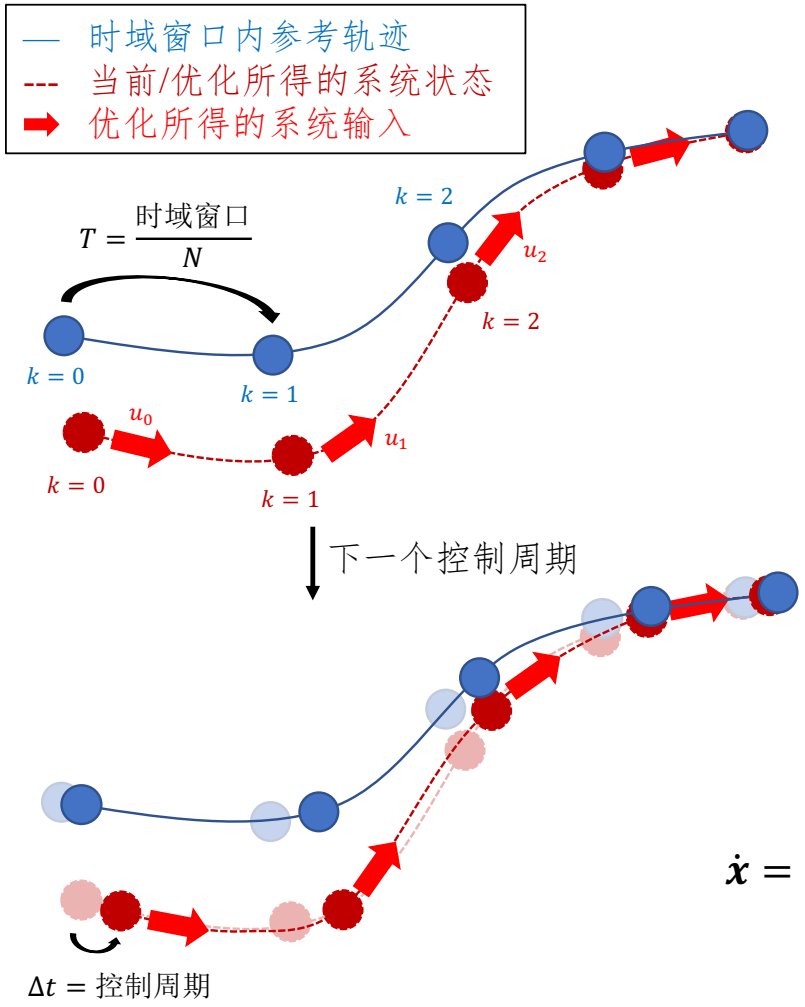


$$\begin{bmatrix} {}_W\boldsymbol{f}_{com} \\ {}_B\boldsymbol{\tau}_{com} \end{bmatrix} = \begin{bmatrix} m \cdot {}_W\dot{\boldsymbol{v}} \\ \boldsymbol{J} \cdot {}_B\dot{\boldsymbol{\omega}} + {}_B\boldsymbol{\omega} \times (\boldsymbol{J} \cdot {}_B\boldsymbol{\omega}) \end{bmatrix}$$

$$\begin{bmatrix} {}_W\boldsymbol{f}_{com} \\ {}_B\boldsymbol{\tau}_{com} \end{bmatrix} = \begin{bmatrix} m\boldsymbol{g} + \text{rotate}({}_B\boldsymbol{f}_a, \boldsymbol{q}) \\ {}_B\boldsymbol{\tau}_a - {}_B\boldsymbol{d}_{com} \times {}_B\boldsymbol{f}_a \end{bmatrix}$$

$$\begin{bmatrix} {}_W\dot{\boldsymbol{v}} \\ {}_B\dot{\boldsymbol{\omega}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{g} + \dfrac{\text{rotate}({}_B\boldsymbol{f}_a, \boldsymbol{q})}{m} \\ \boldsymbol{J}^{-1}\left({}_B\boldsymbol{\tau}_a - {}_B\boldsymbol{d}_{com} \times {}_B\boldsymbol{f}_a - {}_B\boldsymbol{\omega} \times (\boldsymbol{J} \cdot {}_B\boldsymbol{\omega})\right) \end{bmatrix}$$

$$\begin{bmatrix} \dot{\boldsymbol{p}} \\ \dot{\boldsymbol{q}} \\ {}_W\dot{\boldsymbol{v}} \\ {}_B\dot{\boldsymbol{\omega}} \end{bmatrix} = \begin{bmatrix} {}_W\boldsymbol{v} \\ \dfrac{1}{2}\boldsymbol{q} \otimes \begin{bmatrix} 0 \\ {}_B\boldsymbol{\omega} \end{bmatrix} \\ \boldsymbol{g} + \dfrac{\text{rotate}({}_B\boldsymbol{f}_a, \boldsymbol{q})}{m} \\ \boldsymbol{J}^{-1}\left({}_B\boldsymbol{\tau}_a - {}_B\boldsymbol{d}_{com} \times {}_B\boldsymbol{f}_a - {}_B\boldsymbol{\omega} \times (\boldsymbol{J} \cdot {}_B\boldsymbol{\omega})\right) \end{bmatrix}$$

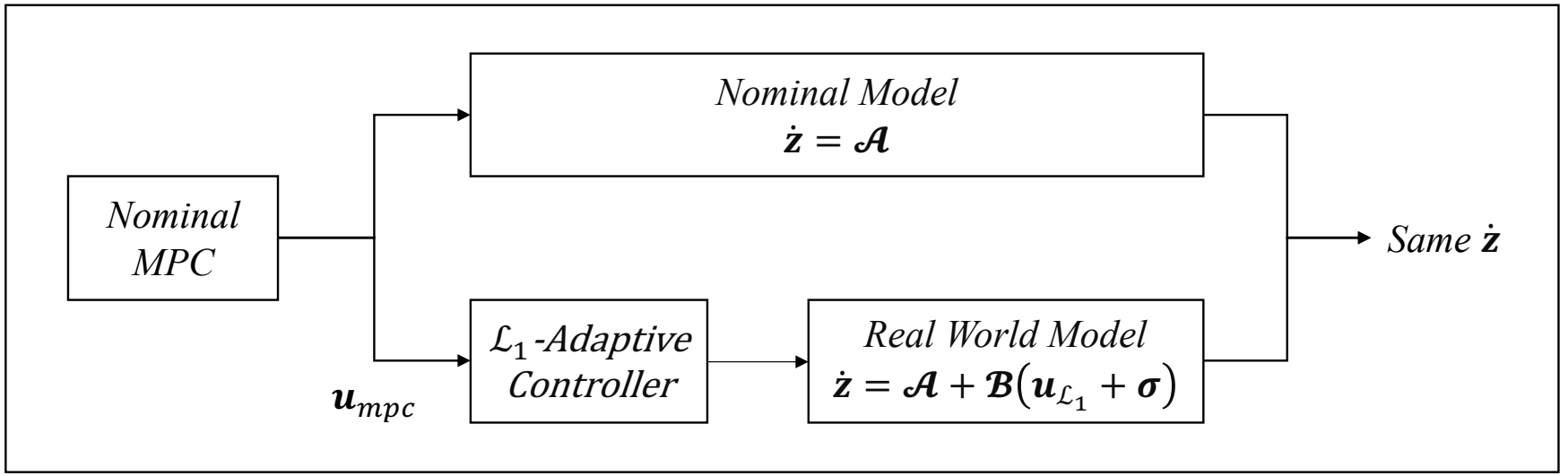


$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{p} \\ \boldsymbol{q} \\ {}_W\boldsymbol{v} \\ {}_B\boldsymbol{\omega} \\ {}_B\boldsymbol{f}_a \\ {}_B\boldsymbol{\tau}_a \end{bmatrix}, \quad \boldsymbol{u} = \begin{bmatrix} {}_B\dot{\boldsymbol{f}}_a \\ {}_B\dot{\boldsymbol{\tau}}_a \end{bmatrix}, \quad \boldsymbol{e} = \begin{bmatrix} \boldsymbol{p}_{err} \\ \boldsymbol{q}_{err} \\ {}_W\boldsymbol{v}_{err} \\ {}_B\boldsymbol{\omega}_{err} \\ {}_B\boldsymbol{f}_a \\ {}_B\boldsymbol{\tau}_a \end{bmatrix}, \quad \boldsymbol{h} = \begin{bmatrix} {}_W\boldsymbol{v} \\ {}_B\boldsymbol{\omega} \\ \boldsymbol{F} \end{bmatrix}$$

$$\min_{[\boldsymbol{u}_0 \cdots \boldsymbol{u}_{N-1}]} \sum_{k=0}^{N-1} \left(\boldsymbol{e}_k^\intercal \boldsymbol{Q} \boldsymbol{e}_k + \boldsymbol{u}_k^\intercal \boldsymbol{R} \boldsymbol{u}_k \right) + \boldsymbol{e}_N^\intercal \boldsymbol{Q}_N \boldsymbol{e}_N$$

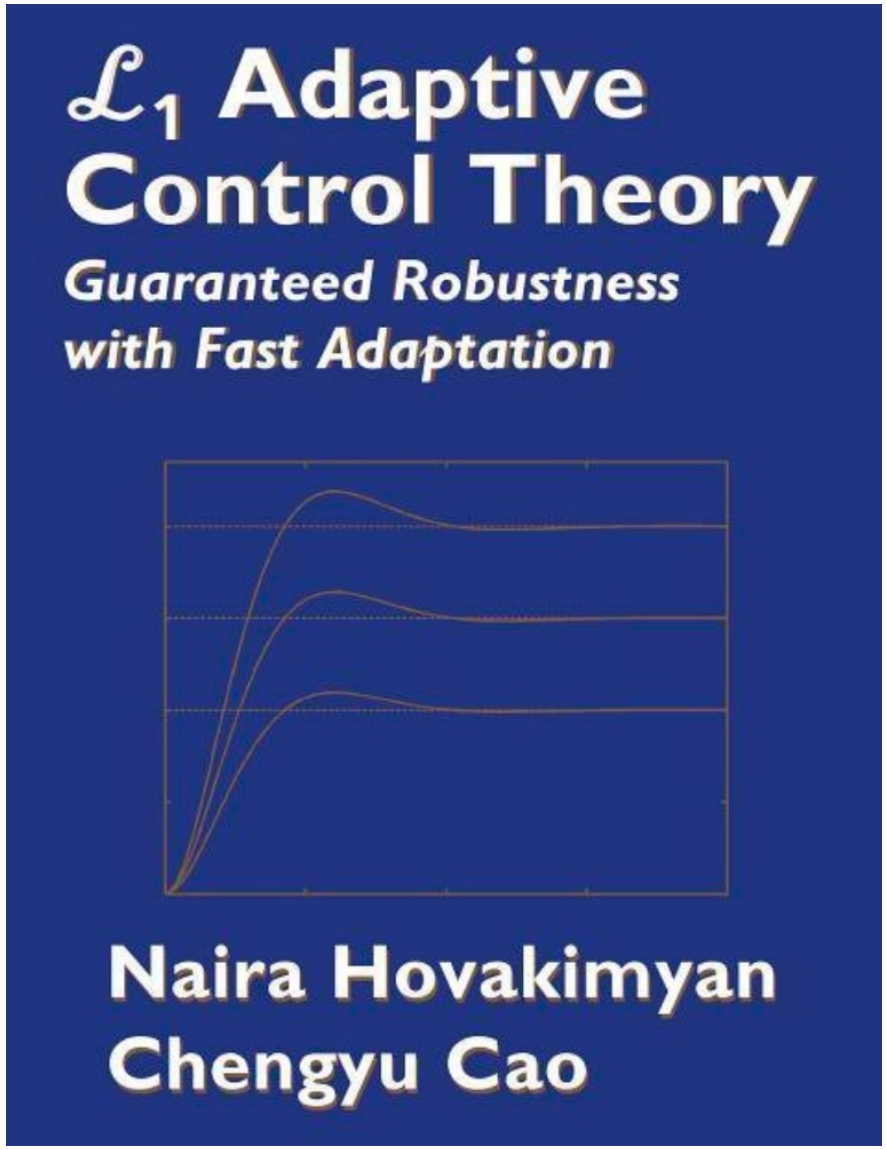
$$\text{s.t.} \begin{cases} \boldsymbol{h}_k \in [\boldsymbol{h}_{lb}, \boldsymbol{h}_{ub}] \\ \boldsymbol{u}_k \in [\boldsymbol{u}_{lb}, \boldsymbol{u}_{ub}] \\ \dot{\boldsymbol{x}} = \text{dyn}(\boldsymbol{x}, \boldsymbol{u}) \\ \boldsymbol{x}_0 = \boldsymbol{x}(t) \end{cases}$$

$$\dot{\boldsymbol{x}} = \begin{bmatrix} {}_W\boldsymbol{v} \\ \frac{1}{2}\boldsymbol{q} \otimes \begin{bmatrix} 0 \\ {}_B\boldsymbol{\omega} \end{bmatrix} \\ \boldsymbol{g} + \frac{\text{rotate}({}_B\boldsymbol{f}_a, \boldsymbol{q})}{m} \\ \boldsymbol{J}^{-1}\left({}_B\boldsymbol{\tau}_a - {}_B\boldsymbol{d}_{com} \times {}_B\boldsymbol{f}_a - {}_B\boldsymbol{\omega} \times (\boldsymbol{J} \cdot {}_B\boldsymbol{\omega}) \right) \\ {}_B\dot{\boldsymbol{f}}_a \\ {}_B\dot{\boldsymbol{\tau}}_a \end{bmatrix} \triangleq \text{dyn}(\boldsymbol{x}, \boldsymbol{u})$$



$$\begin{bmatrix} {}_W\dot{\boldsymbol{v}} \\ {}_B\dot{\boldsymbol{\omega}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{g} + \dfrac{\text{rotate}\left({}_B\boldsymbol{f}_a + {}_B\boldsymbol{f}_{\mathcal{L}_1} + {}_B\boldsymbol{f}_\Delta, \boldsymbol{q}\right)}{m} \\ \boldsymbol{J}^{-1}\left({}_B\boldsymbol{\tau}_a + {}_B\boldsymbol{\tau}_{\mathcal{L}_1} + {}_B\boldsymbol{\tau}_\Delta - {}_B\boldsymbol{d}_{com} \times \left({}_B\boldsymbol{f}_a + {}_B\boldsymbol{f}_{\mathcal{L}_1} + {}_B\boldsymbol{f}_\Delta\right) - {}_B\boldsymbol{\omega} \times (\boldsymbol{J} \cdot {}_B\boldsymbol{\omega})\right) \end{bmatrix}$$

$$\dot{\boldsymbol{z}} = \underbrace{\begin{bmatrix} \boldsymbol{g} + \dfrac{\text{rotate}({}_B\boldsymbol{f}_a, \boldsymbol{q})}{m} \\ \boldsymbol{J}^{-1}\left({}_B\boldsymbol{\tau}_a - {}_B\boldsymbol{d}_{com} \times {}_B\boldsymbol{f}_a - {}_B\boldsymbol{\omega} \times (\boldsymbol{J} \cdot {}_B\boldsymbol{\omega})\right) \end{bmatrix}}_{\mathcal{A}} + \underbrace{\begin{bmatrix} \dfrac{\boldsymbol{R}}{m} & \mathbb{O}_3 \\ -\boldsymbol{J}^{-1}\boldsymbol{D} & \boldsymbol{J}^{-1} \end{bmatrix}}_{\mathcal{B}} \left(\underbrace{\begin{bmatrix} {}_B\boldsymbol{f}_{\mathcal{L}_1} \\ {}_B\boldsymbol{\tau}_{\mathcal{L}_1} \end{bmatrix}}_{u_{\mathcal{L}_1}} + \underbrace{\begin{bmatrix} {}_B\boldsymbol{f}_\Delta \\ {}_B\boldsymbol{\tau}_\Delta \end{bmatrix}}_{\sigma} \right)$$



$\boldsymbol{z} = \hat{\boldsymbol{z}}$ ；

根据当前系统状态更新$\boldsymbol{\mathcal{B}}$和$\boldsymbol{z}$ ；

$\hat{\boldsymbol{\sigma}}_k = -\boldsymbol{\mathcal{B}}^{-1}\left(e^{\boldsymbol{A}T_s} - \mathbb{I}_6\right)^{-1}\boldsymbol{A}e^{\boldsymbol{A}T_s}\tilde{\boldsymbol{z}}_k$；

$\boldsymbol{u}_{\mathcal{L}_1} = \mathrm{LPF}(\hat{\boldsymbol{\sigma}})$ ；

$\boldsymbol{u}_{\mathcal{L}_1} + \boldsymbol{u}_{mpc}$ 输出给下游模块；

$\dot{\hat{\boldsymbol{z}}} = \boldsymbol{\mathcal{A}} + \boldsymbol{\mathcal{B}}\left(\boldsymbol{u}_{\mathcal{L}_1} + \hat{\boldsymbol{\sigma}}\right) + \boldsymbol{A}\tilde{\boldsymbol{z}}$ ；

$\hat{\boldsymbol{z}}_{k+1} = \hat{\boldsymbol{z}}_k + T_s\dot{\hat{\boldsymbol{z}}}$ ；

$$
\begin{aligned}
&\boldsymbol{\mathcal{B}}^{-1} \\
&= \begin{bmatrix} \dfrac{\boldsymbol{R}}{m} & \mathbb{O}_3 \\ -\boldsymbol{J}^{-1}\boldsymbol{D} & \boldsymbol{J}^{-1} \end{bmatrix}^{-1} \\
&= \begin{bmatrix} \left(\dfrac{\boldsymbol{R}}{m}\right)^{-1} & \mathbb{O}_3 \\ m\boldsymbol{D}\boldsymbol{R}^{-1} & \boldsymbol{J} \end{bmatrix} \\
&= \begin{bmatrix} m\boldsymbol{R}^{\mathsf{T}} & \mathbb{O}_3 \\ m\boldsymbol{D}\boldsymbol{R}^{\mathsf{T}} & \boldsymbol{J} \end{bmatrix}
\end{aligned}
$$