Time-Varying Manual Control Identification in a Stall Recovery Task under Different Simulator Motion Conditions

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This paper adds data to help develop simulator motion guidelines for stall recovery training by identifying time-varying manual control behavior in a stall recovery task under different simulator motion conditions. A study was conducted in the NASA Ames Vertical Motion Simulator, where seventeen general aviation pilots performed a stall recovery task. Pilots had to follow a flight director through four stages of the stall recovery task. A time-varying identification method was used to quantify how pilots weigh position and velocity information throughout different stages of the task, in both roll and pitch. Four motion configurations were used: no motion, generic hexapod motion, enhanced hexapod motion and full motion. Pilot performance was highest for the enhanced hexapod and full motion conditions in both roll and pitch, and the lowest for the condition with no motion. The time-varying identification method revealed that, in the roll axis, pilot position gain did not significantly change between time segments, but was the lowest for the condition with no motion. The pilot velocity gain was significantly different between motion conditions, the largest difference being found at the beginning of the stall. The enhanced hexapod motion condition had the highest pilot velocity gain. In the pitch axis, the pilot position gain was significantly different between time segments but not between motion conditions. The pitch pilot velocity gain was highest for the full motion condition and increased at the beginning of the stall, but did not change significantly for the other motion conditions. Overall, pilot control behavior under enhanced hexapod motion was more similar to that under full aircraft motion compared to standard hexapod motion. This indicates that motion cueing on hexapod simulators might be improved for stall recovery training by using the enhanced hexapod motion developed in previous experiments.

TIME-VARYING MANUAL CONTROL IDENTIFICATION IN A STALL RECOVERY TASK UNDER DIFFERENT SIMULATOR MOTION CONDITIONS

AIAA-2018-2936

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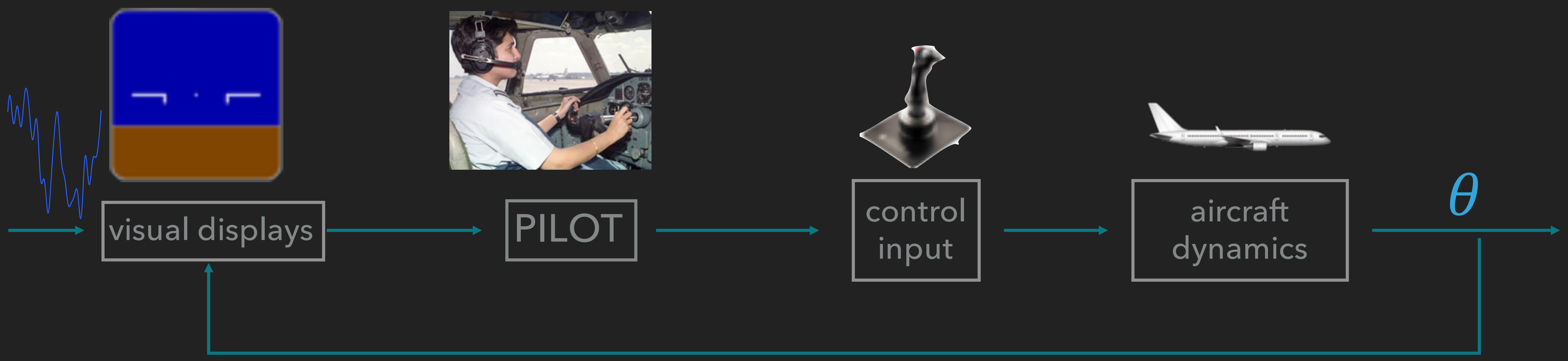
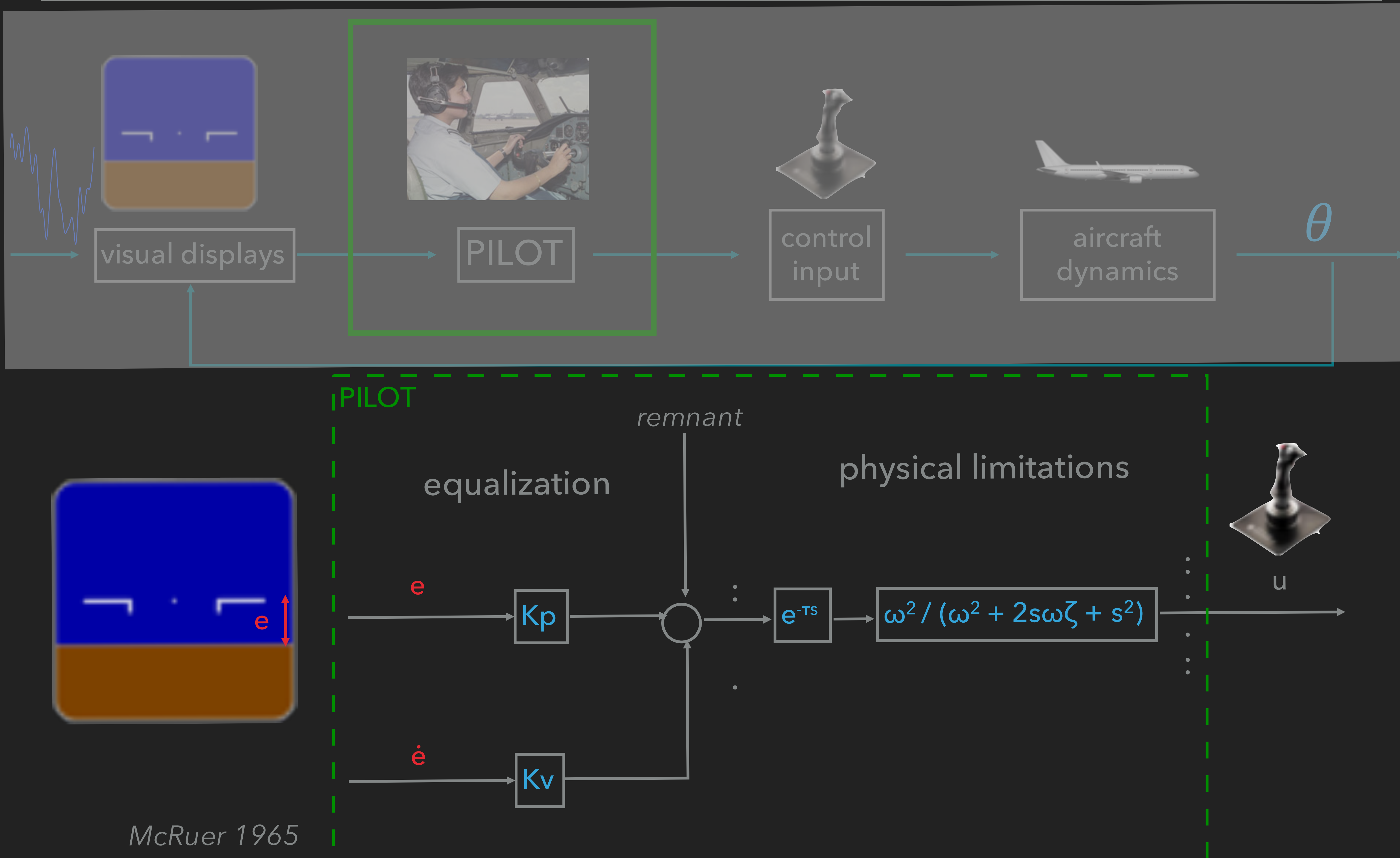
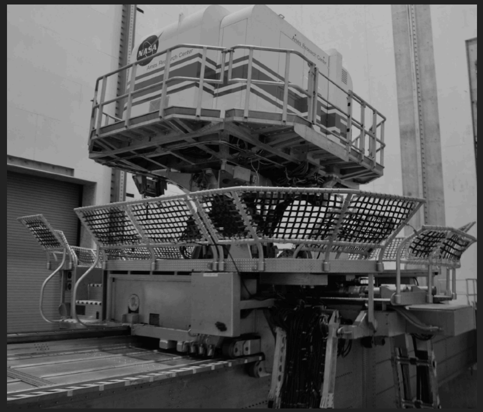
BACKGROUND (1) – CYBERNETICS



BACKGROUND (1) – CYBERNETICS



BACKGROUND (2) – MOTION CUEING FOR STALL RECOVERY



single-axis, ***time-invariant*** tasks

Effects of False Tilt Cues on the Training of Manual Roll Control Skills
AIAA - 2015 - 0655

Effects of Heave Motion Components on Pitch Control Behavior
AIAA - 2016 - 3371

Effects of Motion Cues on the Training of Multi-Axis Manual Control Skills
AIAA - 2017 - 3473

Time-Varying Manual Control Identification in a Stall Recovery Task Under Different Simulator Motion Conditions
AIAA - 2018 - 2936

multi-axis, ***time-varying*** tasks

Time-Varying Pilot Control Behavior Identification using MLE
AIAA - 2012 - 4793

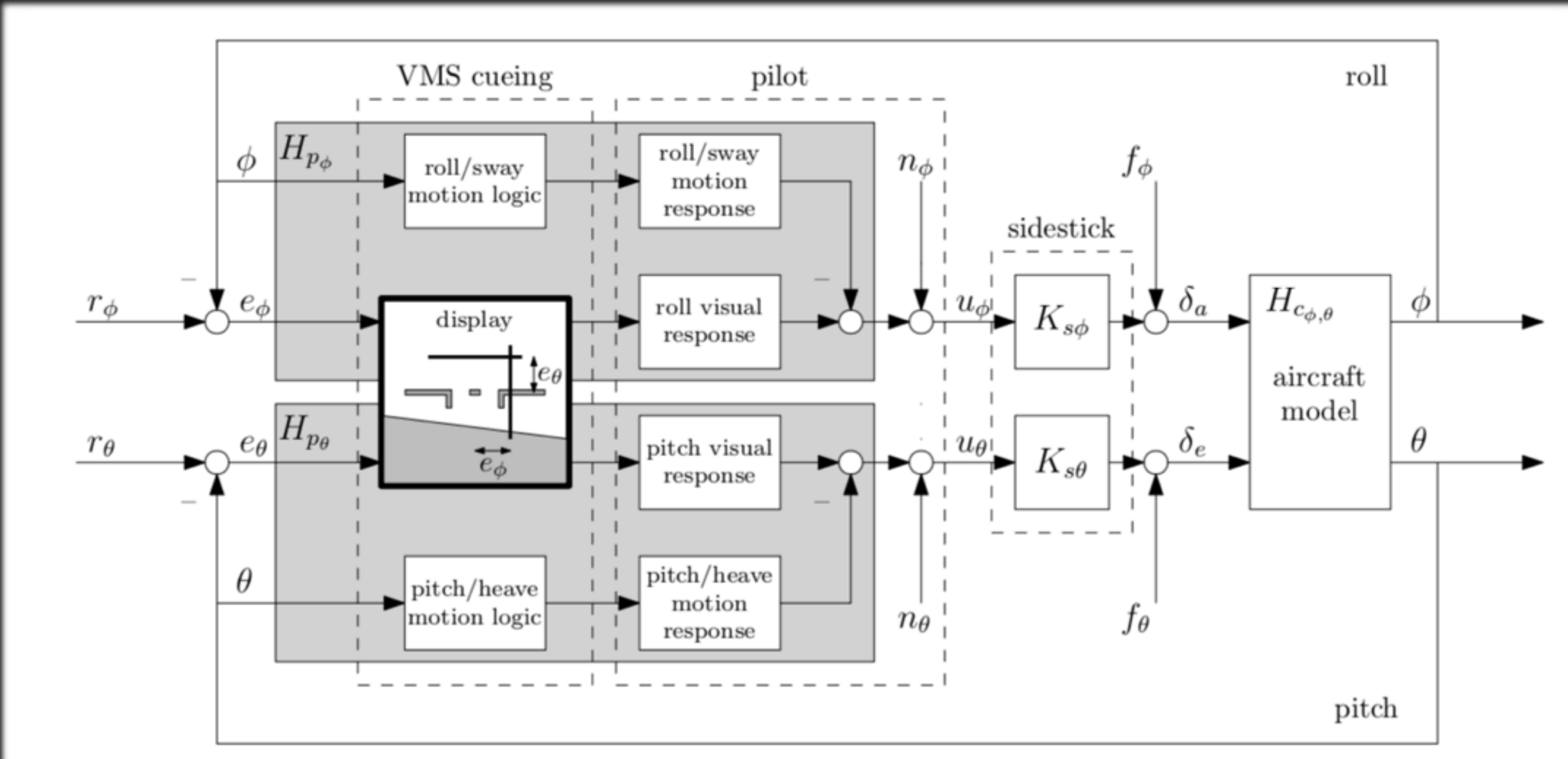
Multi-Axis Tracking Tasks with Time-Varying Motion
AIAA - 2014 - 0810

Time-Varying Pilot Control Identification using Kalman Filtering
AIAA - 2017 - 3666

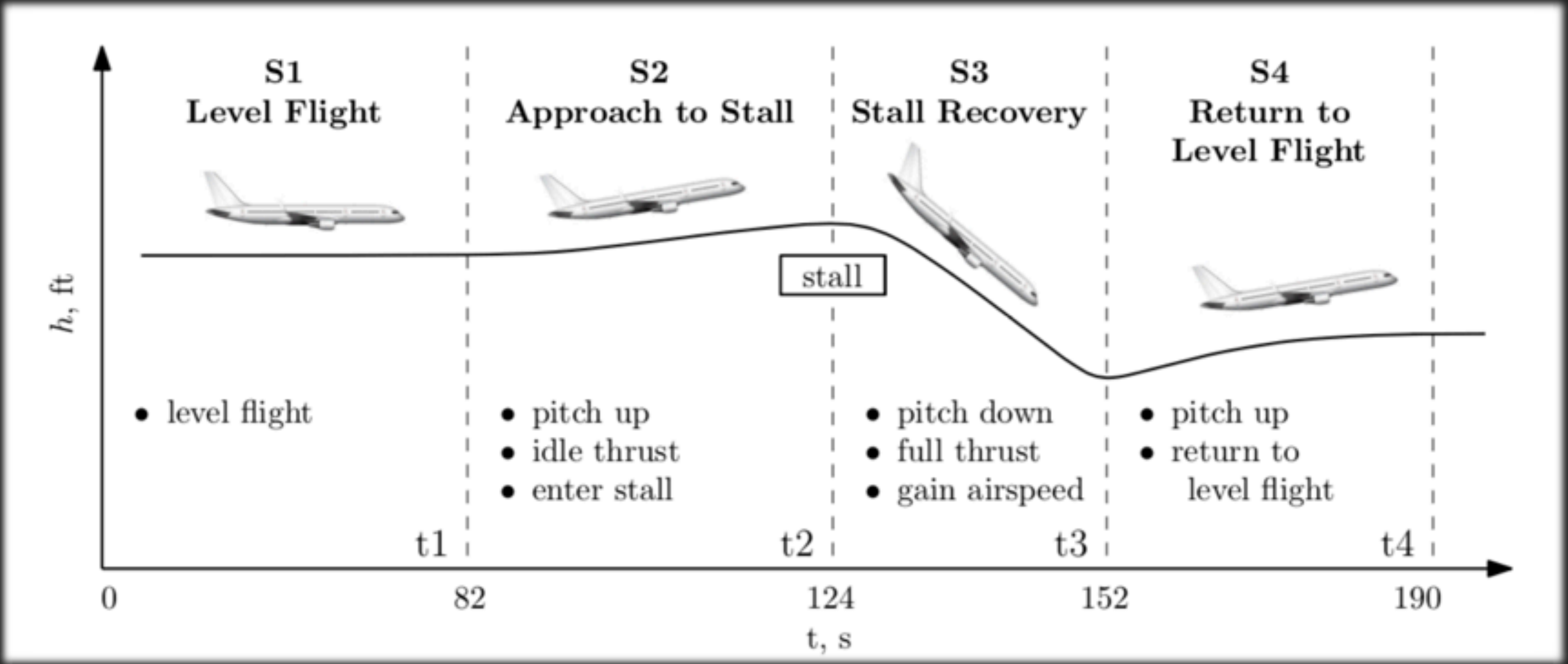
RESEARCH QUESTIONS – STALL RECOVERY TASK

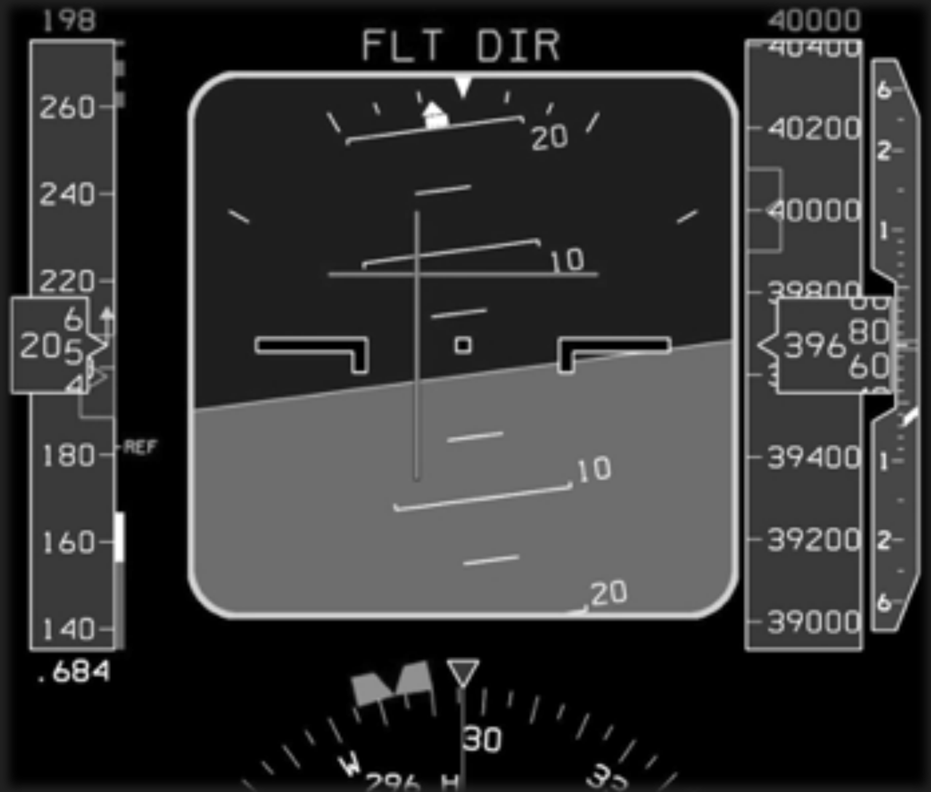
1. What are the effects of different simulator motion settings on human manual control?
2. How do pilots adapt their control strategies through different stages of stall recovery?
3. Are differences in motion the same during different stages of stall recovery?

DOUBLE-AXIS COMPENSATORY TASK



FLIGHT TASK


S1
Level Flight
S2
Approach to Stall
S3
Stall Recovery
S4
Return to
Level Flight
h, ft
stall
• level flight
• pitch up
• idle thrust
• enter stall
• pitch down
• full thrust
• gain airspeed
• pitch up
• return to
level flight
t1
t2
t3
t4
0
82
124
152
190
t, s


FLT DIR
198
260
240
220
205
180
160
140
.684
REF
40000
40200
40000
39400
39200
39000
396
20
10

MOTION CONDITIONS

No Motion(NM)

no motion cues

Generic Hexapod (GH)

typical motion by training hexapod simulators

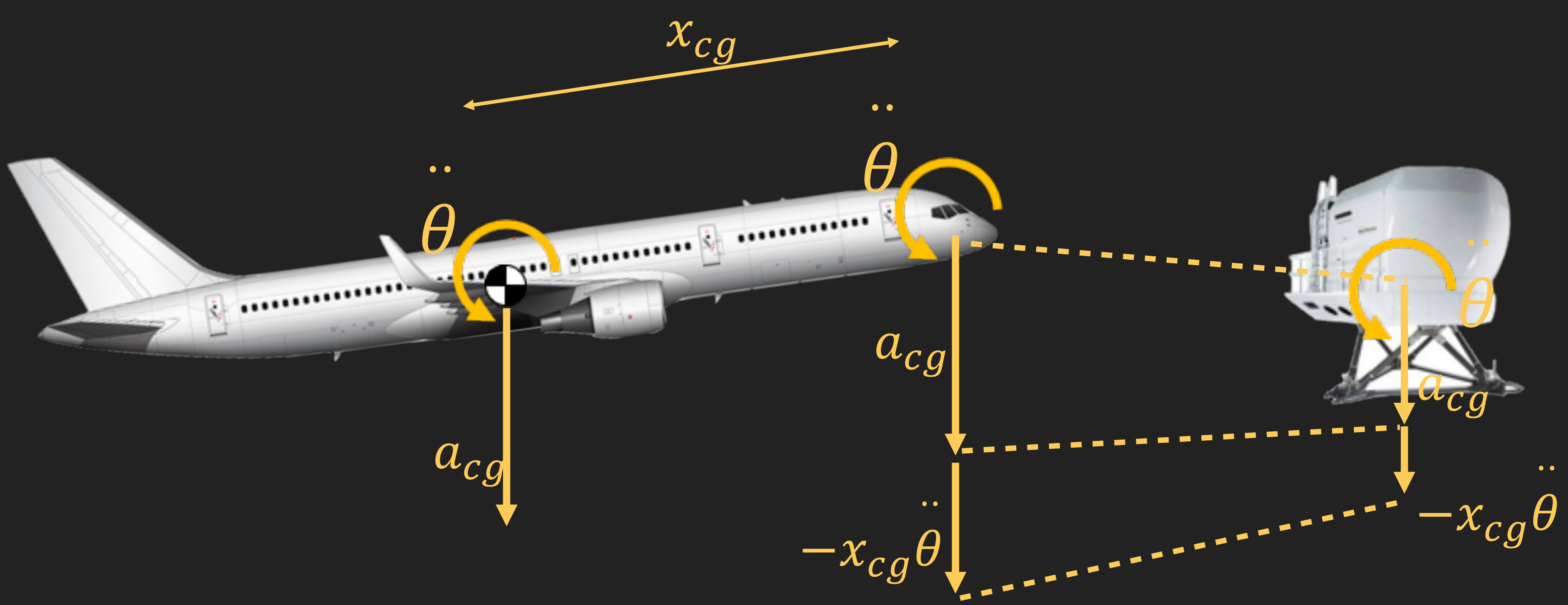
Enhanced Hexapod (EH)

eliminate translational acceleration of c.g.

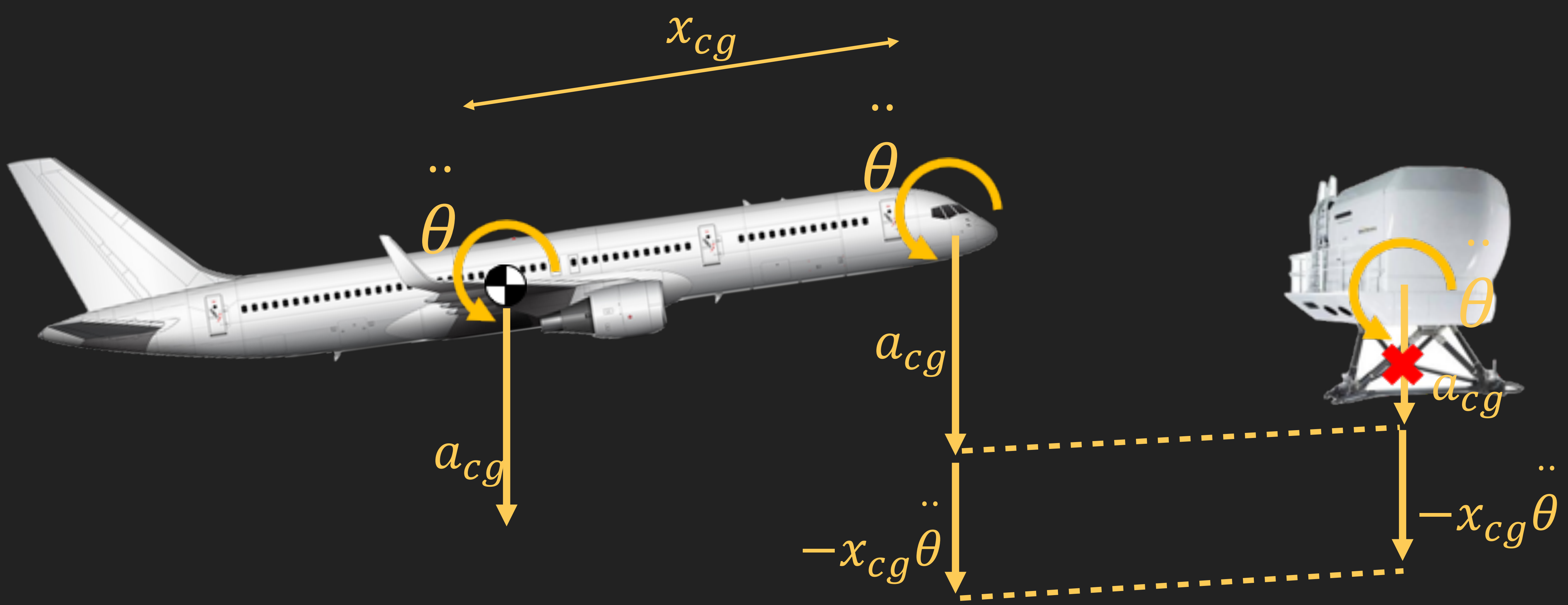
Full Motion (FM)

full aircraft motion

GENERIC HEXAPOD (GH)



ENHANCED HEXAPOD (EH)



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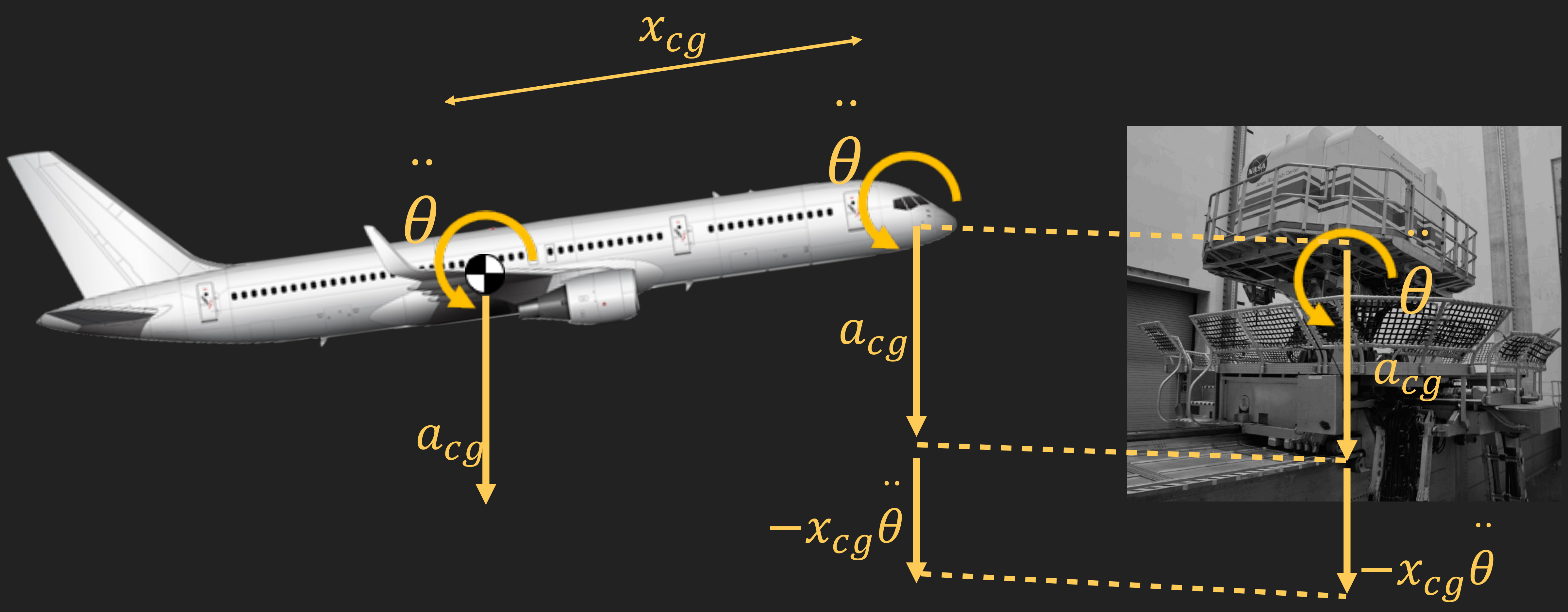
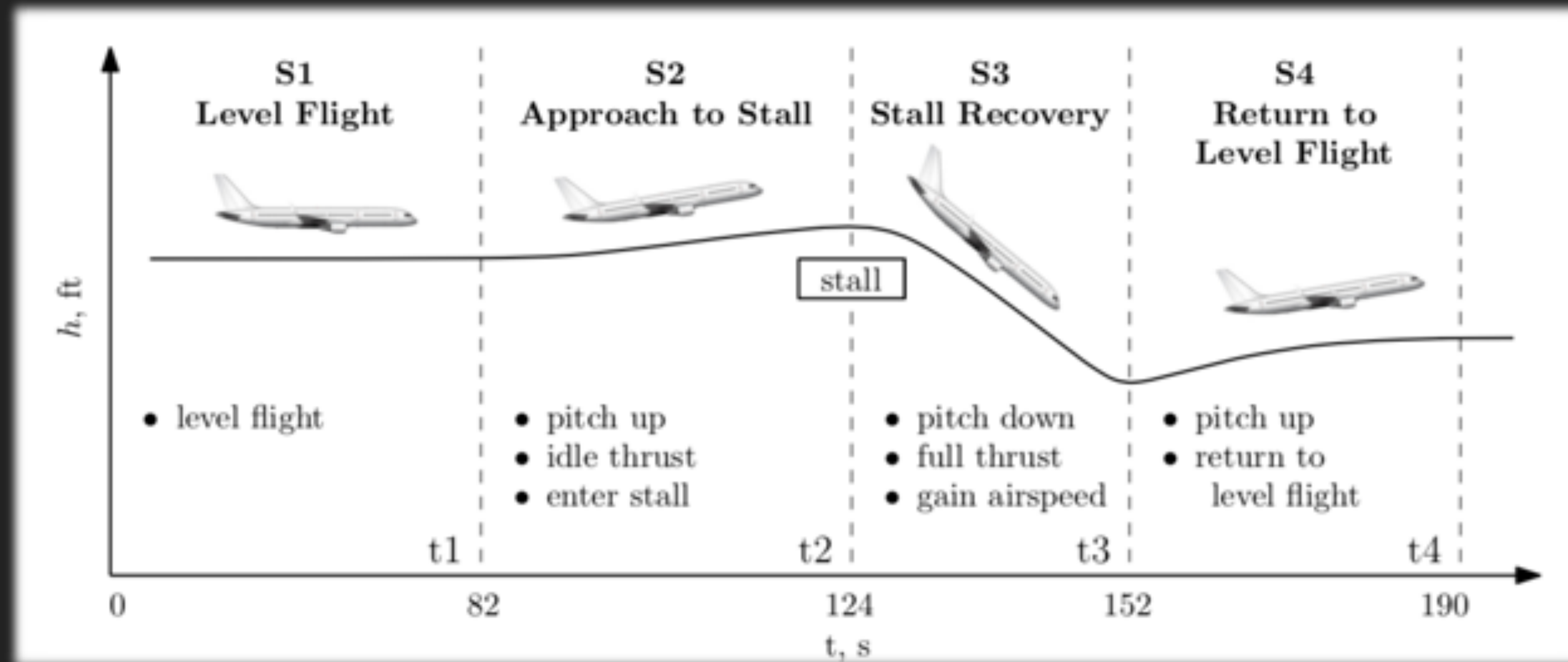
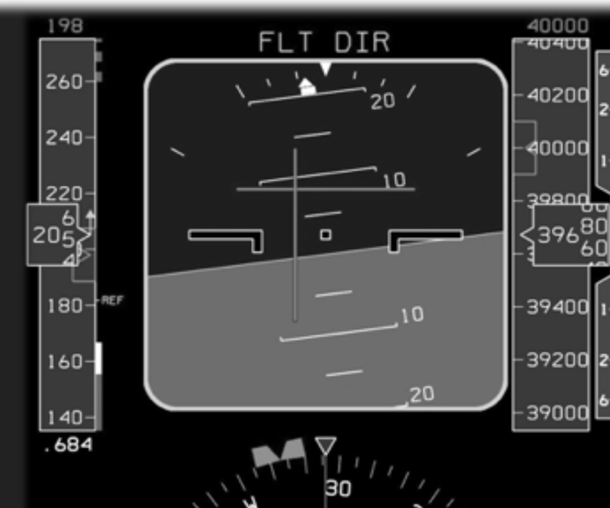
FULL MOTION (FM)

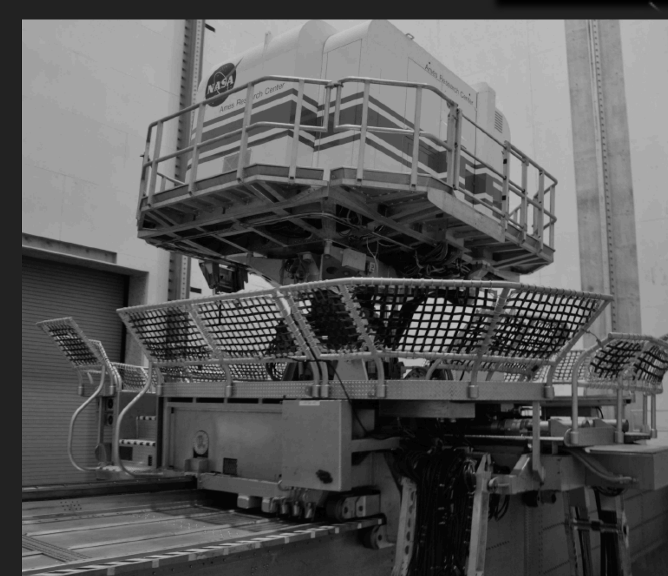


EXPERIMENT DESIGN

- *17 general aviation pilots*
- *32 (8x4 runs)*
- *Vertical Motion Simulator*
- *GTM model*
- *dependent measures*
  - *human manual control parameters*
  - *open-loop stability and phase margin*
  - *RMS error and control activity*







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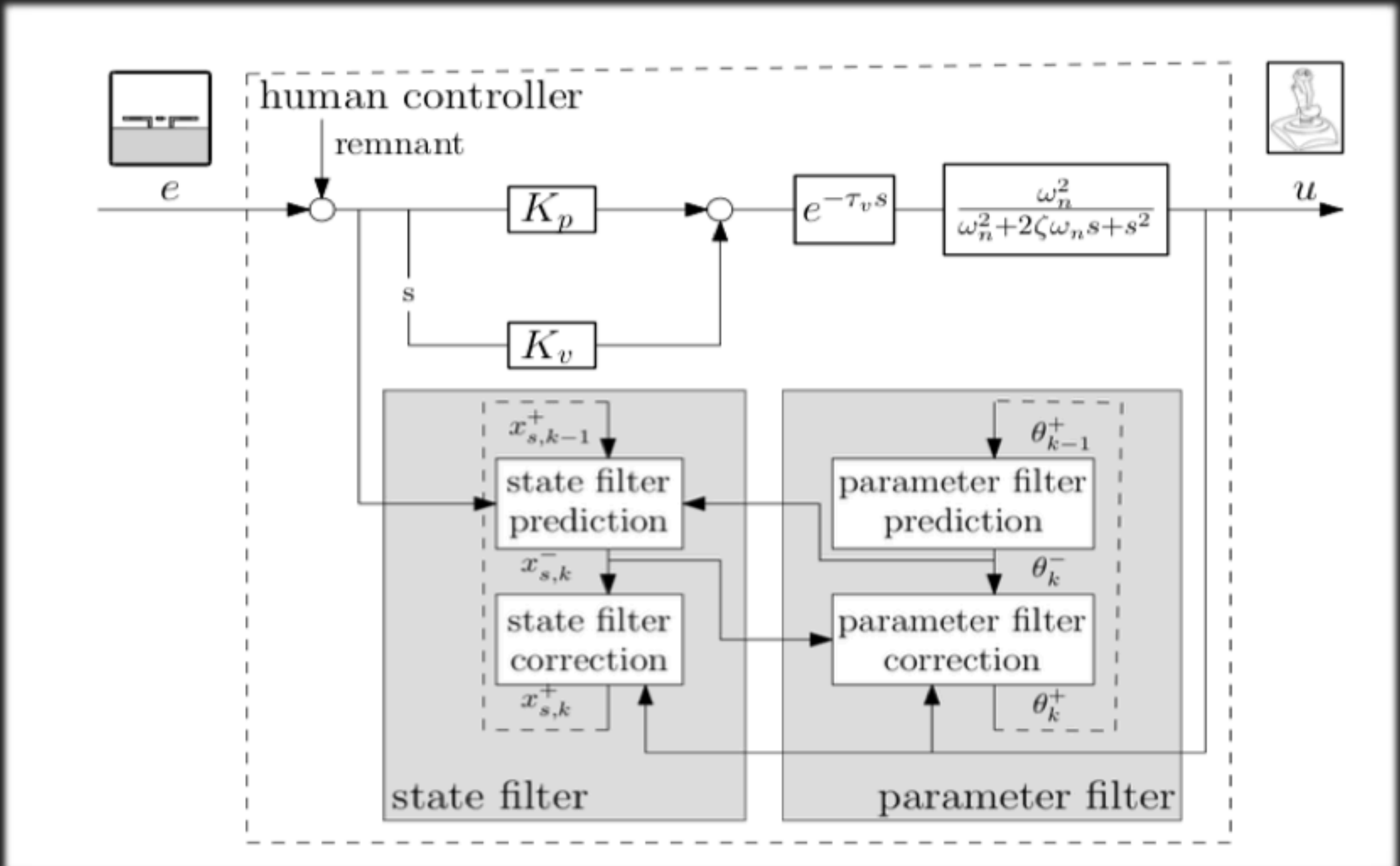
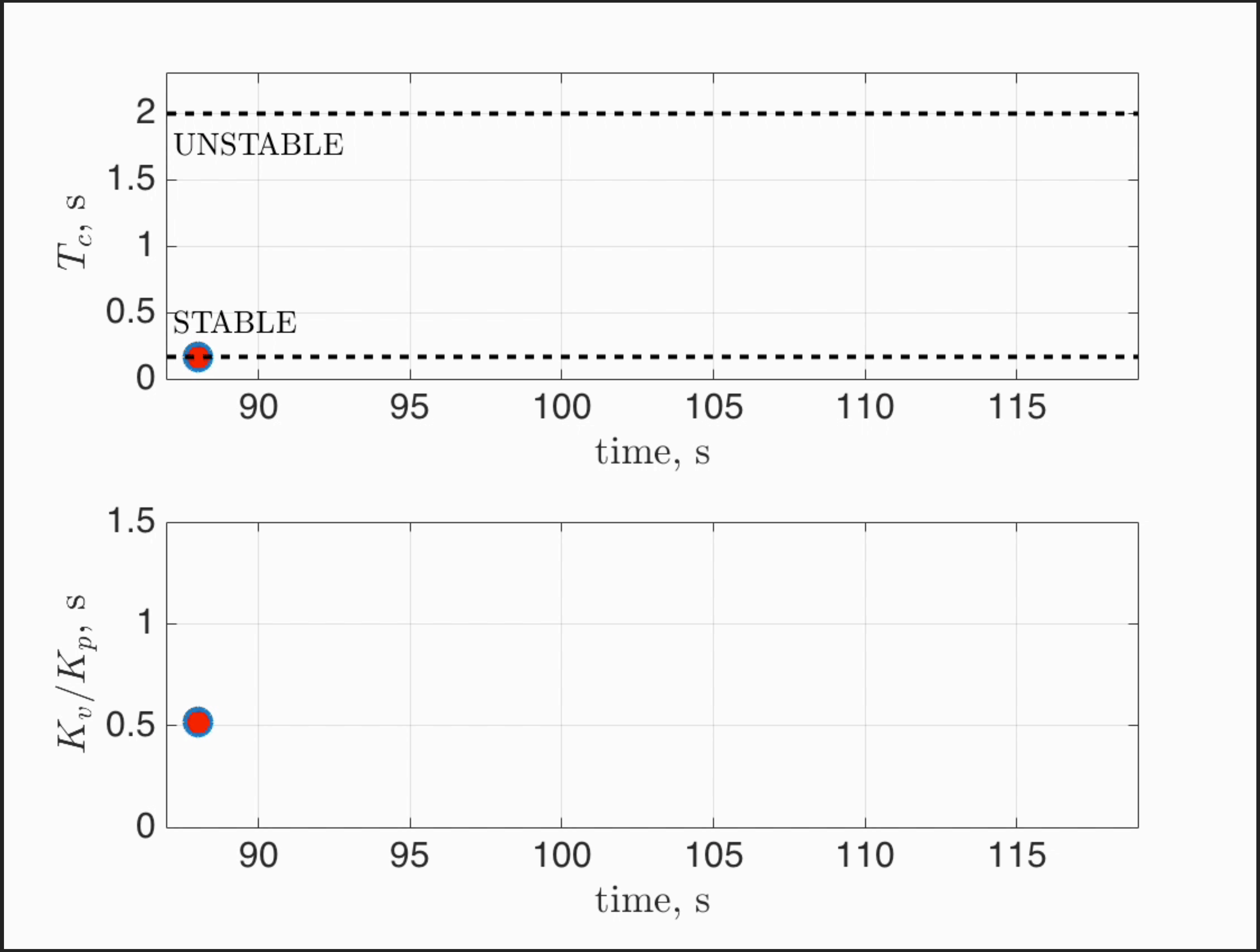
DUAL EXTENDED KALMAN FILTER

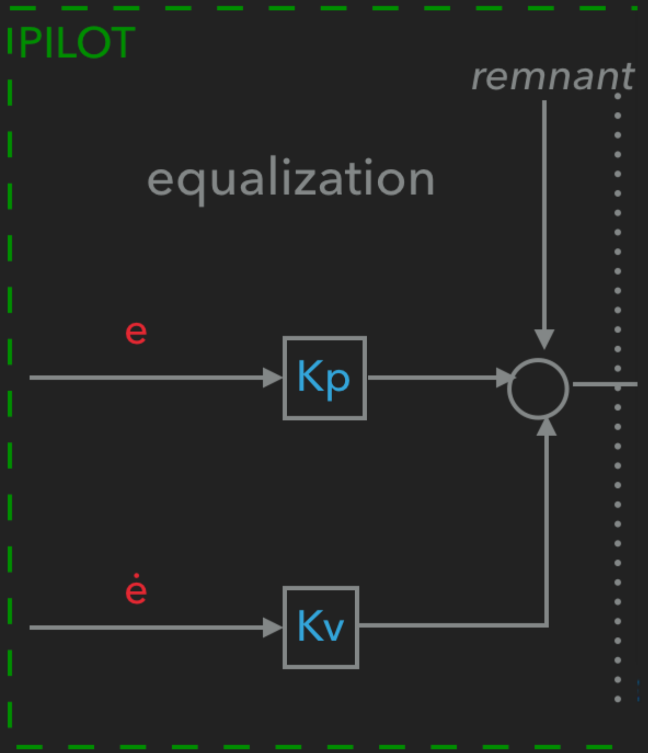


- *two extended Kalman filters running in parallel*
- ***state filter**: estimates equalization parameters*
- ***parameter filter:** estimates neuromuscular parameters*
- *constant time delay*

DUAL EXTENDED KALMAN FILTER - EXAMPLE

$$H_c(s,t) = \frac{K_c}{s(T_c(t)s + 1)}$$

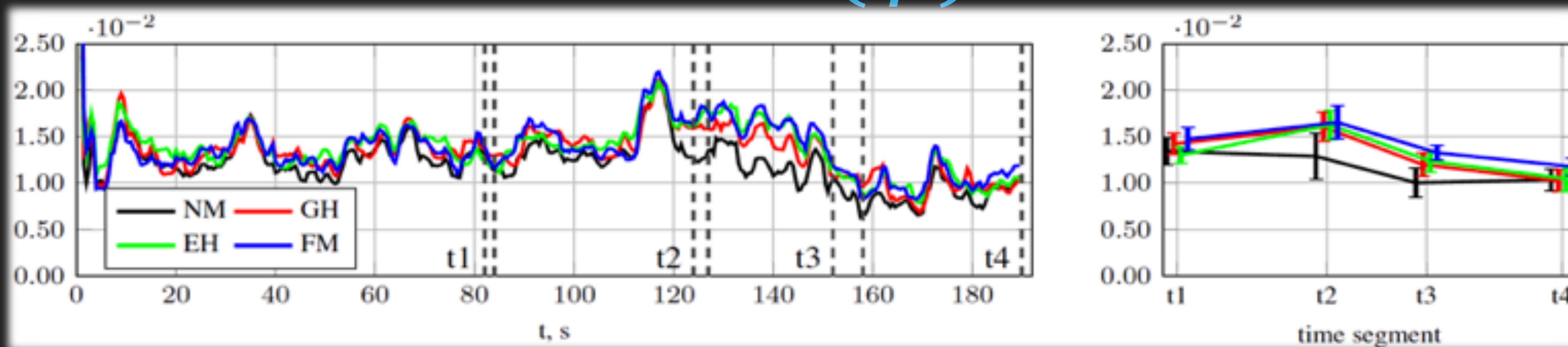




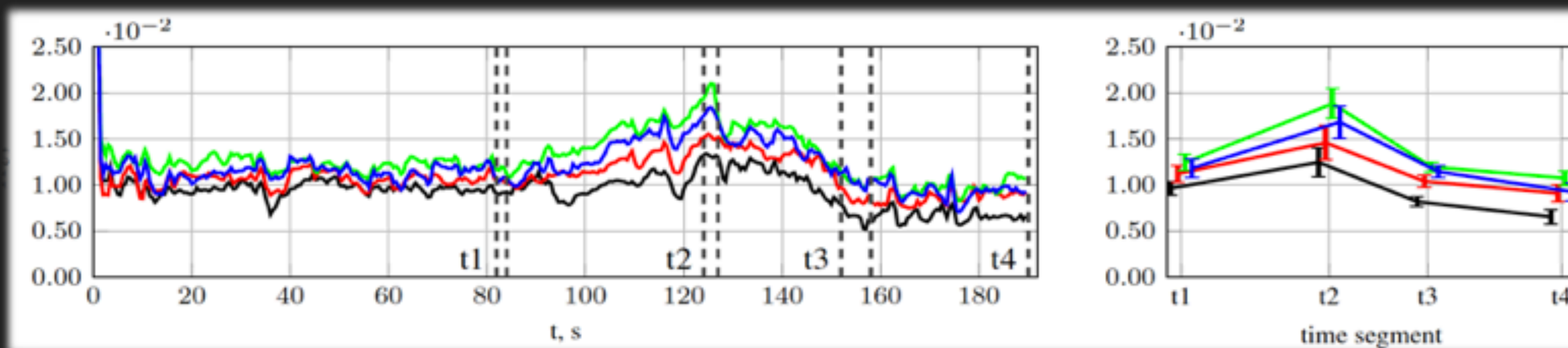
RESULTS – POSITION AND VELOCITY GAINS

$Roll(\phi)$

K_p

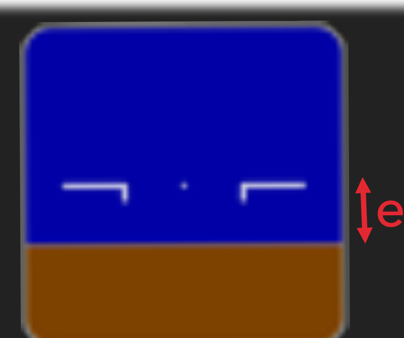


K_v



- *position gain:*
  - *lower for NM in t2(stall) and t3(dive)*
  - *no differences between time segments*

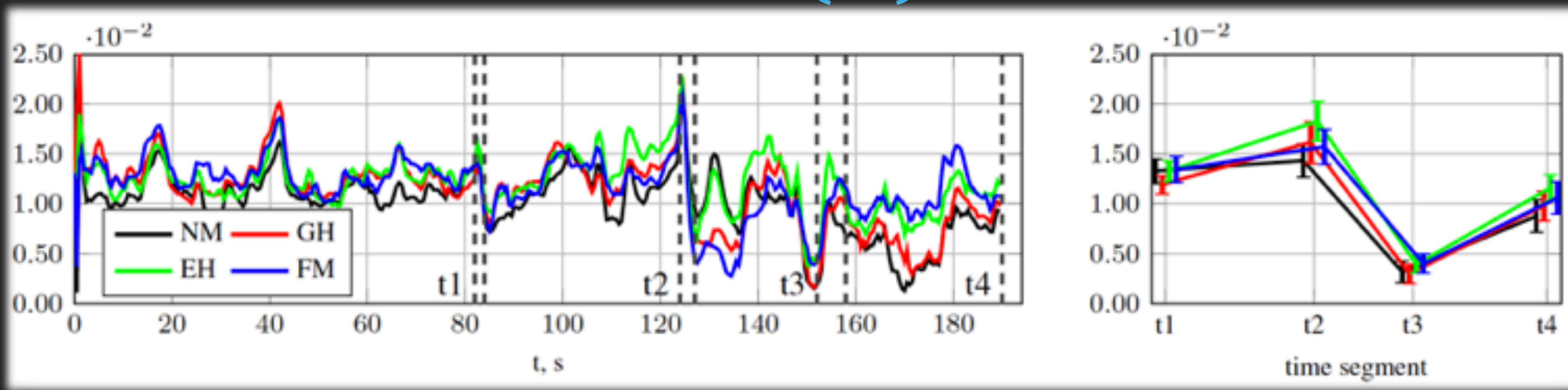
- *velocity gain:*
  - *highest for EH*
  - *increases towards stall (t2); lower after recovery (t4)*
  - *highest difference at stall (t2)*



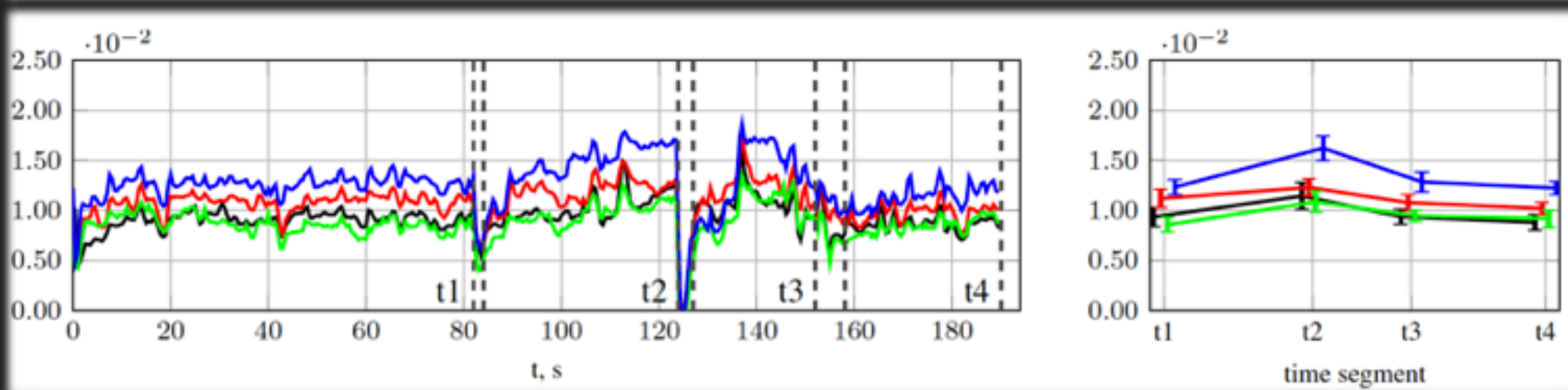
RESULTS - POSITION AND VELOCITY GAINS

$Pitch(\theta)$

K_p



K_v



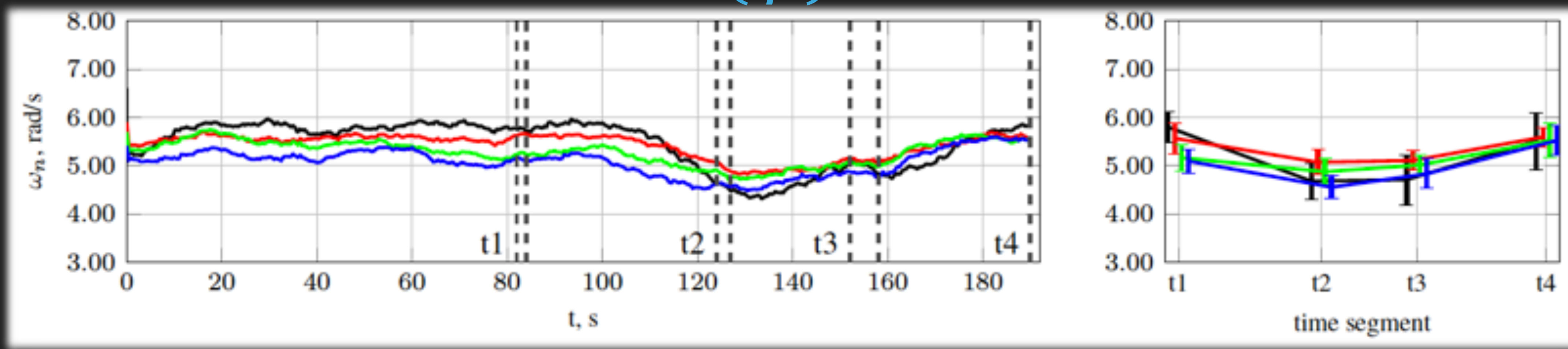
- *position gain:*
  - *no difference between motion conditions*
  - *decreased at (t3)*

- *velocity gain:*
  - *highest for FM*
  - *higher at the beginning of stall for FM*

RESULTS – NEUROMUSCULAR FREQUENCY

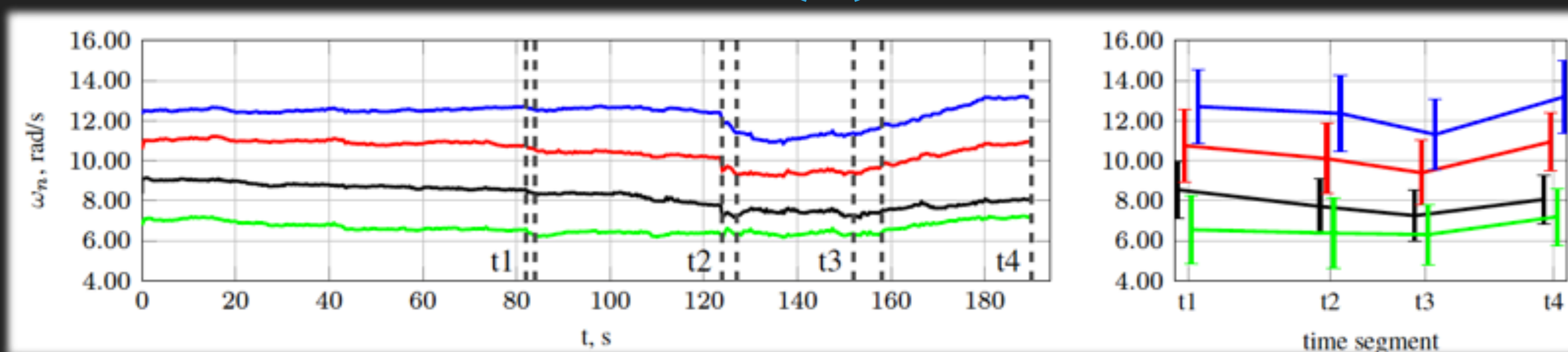
$Roll(\phi)$

ω_n



$Pitch(\theta)$

ω_n



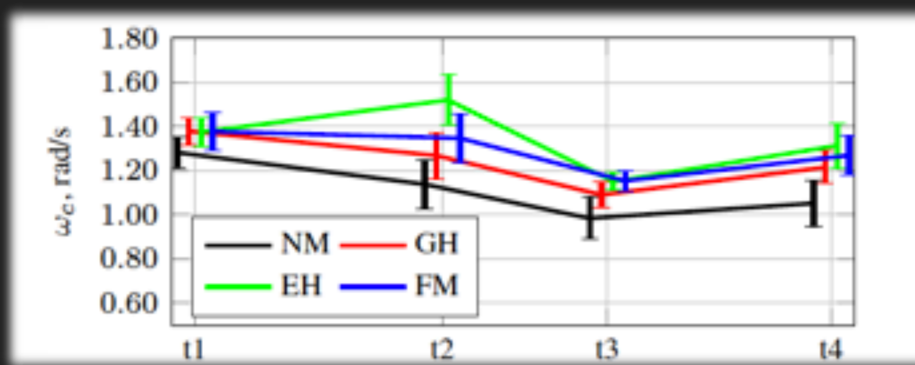
- *roll:*
  - *no difference between motion conditions*
  - *decreases in stall and dive*

- *pitch:*
  - *highest for FM, lowest for NM*
  - *decreases in stall and dive*

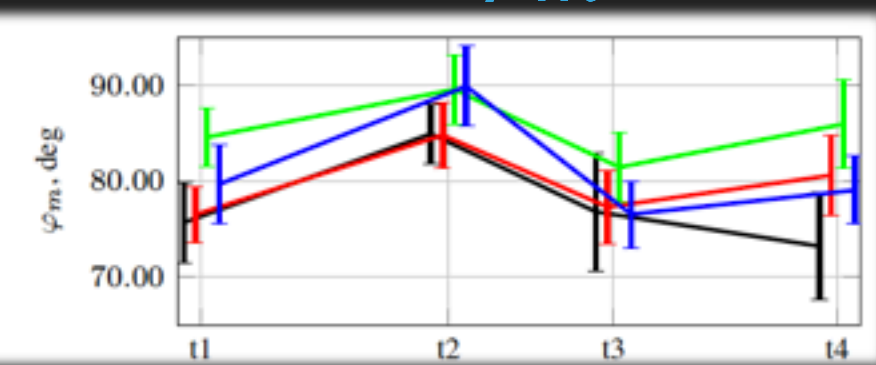
RESULTS - OPEN-LOOP CHARACTERISTICS

ϕ

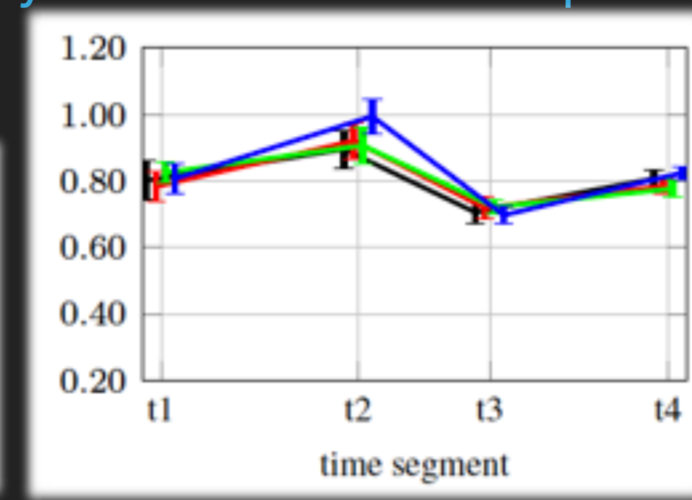
ω_c



φ_m

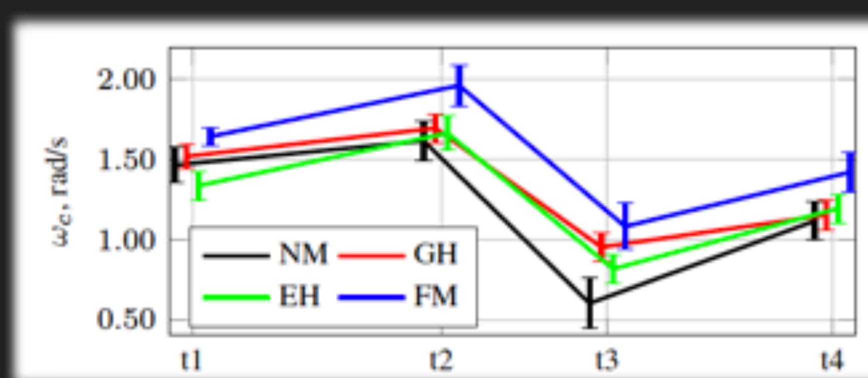


dynamics crossover frequency

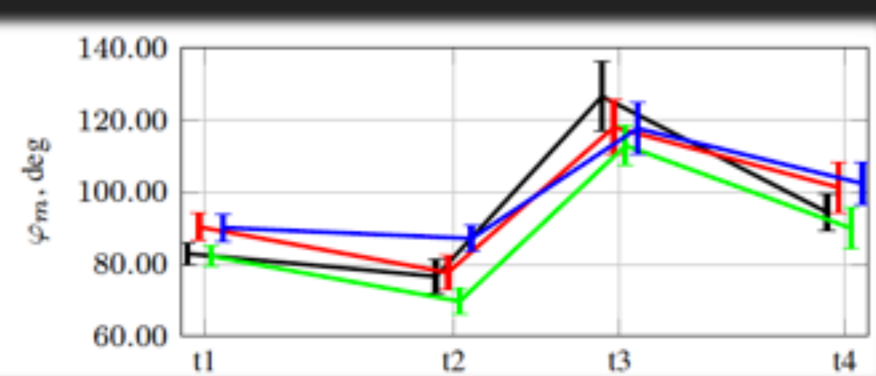


θ

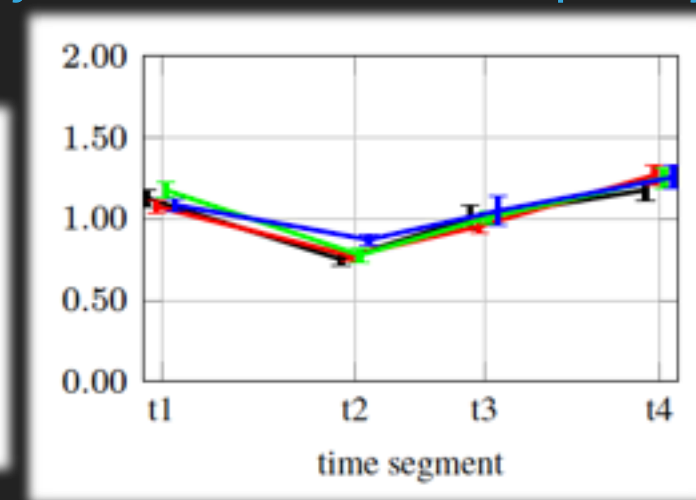
ω_c



φ_m



dynamics crossover frequency



- *roll:*
  - *crossover frequency higher with motion*
  - *crossover frequency lowest in the dive(t3)*
  - *phase margin highest for EH*
  - *phase margin highest at stall (t2)*
- *pitch:*
  - *crossover frequency highest for FM*
  - *crossover frequency lowest at the end of the dive(t3)*
  - *phase margin lowest for EH*
  - *highest at the end of dive(t3)*

CONCLUSIONS

- multi-axis time-varying pilot identification in a stall recovery task
- the *enhanced hexapod* condition was the closest to the *full motion condition*
- pilot manual control behavior was different in roll and pitch axes
- differences in motion larger closer to stall point
- ***adaptive motion cueing***

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EXTRA SLIDES

STATE SPACE REPRESENTATION (1)

$$(K_p(t) + K_v(t)s)e^{-\tau_v s}\frac{\omega_n^2(t)}{s^2 + 2\zeta_n(t)\omega_n(t)s + \omega_n^2(t)}$$

$$\begin{aligned}\dot{\boldsymbol{x}}_{\boldsymbol{s}}(t) &= f(\boldsymbol{x}_{\boldsymbol{s}}(t), e(t), \boldsymbol{\theta}(t)) + \boldsymbol{w}_{\boldsymbol{s}}(t)\\ u(t) &= g(\boldsymbol{x}_{\boldsymbol{s}}(t), \boldsymbol{\theta}(t)) + v(t)\end{aligned}$$

$$\begin{aligned}\dot{\boldsymbol{\theta}}(t) &= \boldsymbol{w}_{\boldsymbol{p}}(t)\\ u(t) &= g(\boldsymbol{x}_{\boldsymbol{s}}(t), \boldsymbol{\theta}(t)) + v(t)\end{aligned}$$

$$\boldsymbol{x}_{\boldsymbol{s}} = \begin{bmatrix} x_{s,1} & x_{s,2} & x_{s,3} & x_{s,4} & x_{s,5} & K_p & K_v \end{bmatrix}^T$$

$$\boldsymbol{\theta} = \begin{bmatrix} \omega_n & \zeta_n & \tau_v \end{bmatrix}^T$$

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STATE SPACE REPRESENTATION (2)

$$Q_p = diag([0.1\omega_{n,0}\ 0.1\zeta_{n,0}\ 0.1\tau_{v,0}])$$

$$Q_s(k) = diag\left(\begin{bmatrix}0 & 0 & 0 & 0 & q^2\sigma^2_{e(k-5/\Delta t:k)} & K_{p,0}\ K_{v,0}\end{bmatrix}\right)$$

$$f(\boldsymbol{x_s}, e, \boldsymbol{\theta}) = \begin{bmatrix} x_{s,2} \\ x_{s,3} \\ x_{s,4} \\ x_{s,5} \\ e - x_{s,3}(12\omega_n^2\tau_v^2 + 120\zeta_n\omega_n\tau_v + 120)/\tau_v^3 - x_{s,2}(60\tau_v\omega_n^2 + 240\zeta_n\omega_n)/\tau_v^3 - \\ \cdots - x_{s,4}(\omega_n^2\tau_v^3 + 24\zeta_n\omega_n\tau_v^2 + 60\tau_v)/\tau_v^3 - x_{s,5}(2\zeta_n\omega_n\tau_v^3 + 12\tau_v^2)/\tau_v^3 - 120x_{s,1}\omega_n^2/\tau_v^3 \\ 0 \\ 0 \end{bmatrix}$$

$$g(\boldsymbol{x_s}, \boldsymbol{\theta}) = \begin{bmatrix} x_{s,3}(12K_p\omega_n^2\tau_v^2 - 60K_v\omega_n^2\tau_v)/\tau_v^3 - K_v\omega_n^2 x_{s,5} + x_{s,2}(120K_v\omega_n^2 - 60K_p\omega_n^2\tau_v)/\tau_v^3 - \\ \cdots - x_{s,4}(K_p\omega_n^2\tau_v^3 - 12K_v\omega_n^2\tau_v^2)/\tau_v^3 + 120K_p\omega_n^2 x_{s,1}/\tau_v^3 \end{bmatrix}$$

KALMAN EQUATIONS

Parameter filter prediction:

$$\boldsymbol{\theta}_k^- = \boldsymbol{\theta}_{k-1}^+$$
$$P_{p,k}^- = \Phi_{p,k-1} P_{p,k-1}^+ \Phi_{p,k-1}^T + \Gamma_{p,k-1} Q_p \Gamma_{p,k-1}^T$$

State filter prediction:

$$\boldsymbol{x}_{s,k}^- = \boldsymbol{x}_{s,k-1}^+ + f(\boldsymbol{x}_{s,k-1}^+, e_{k-1}, \theta_k^-)\Delta t$$
$$P_{s,k}^- = \Phi_{s,k-1} P_{s,k-1}^+ \Phi_{s,k-1}^T + \Gamma_{s,k-1} Q_s \Gamma_{s,k-1}^T$$

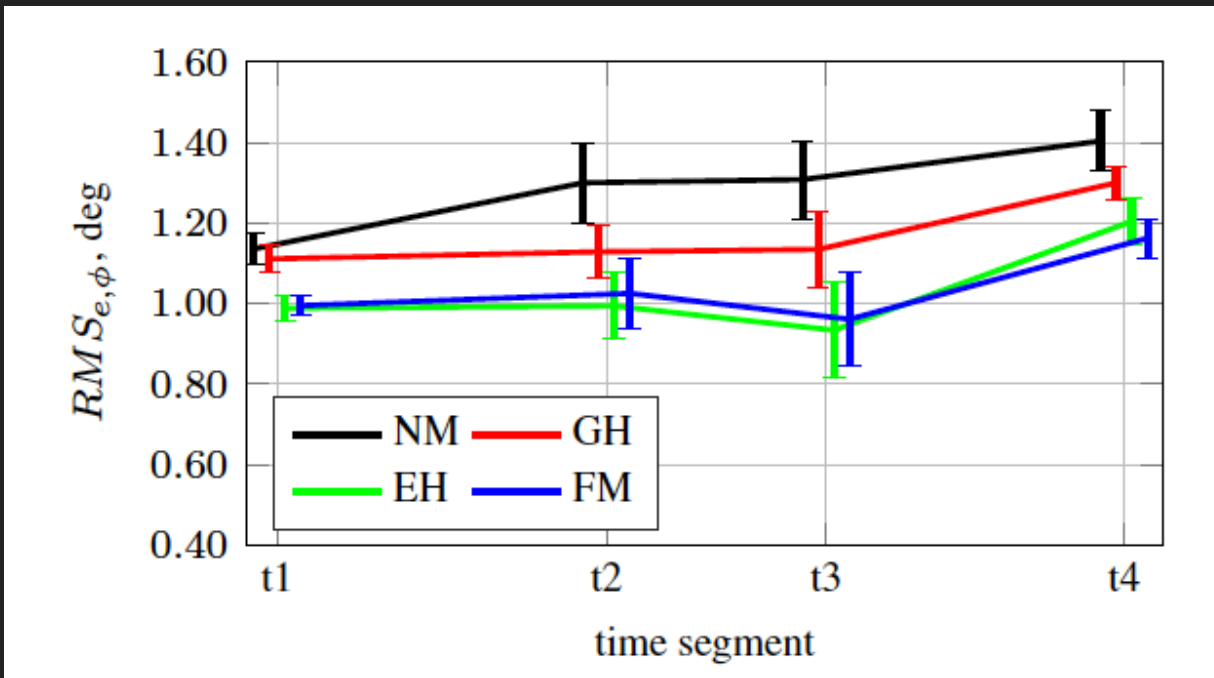
State filter (partial) correction:

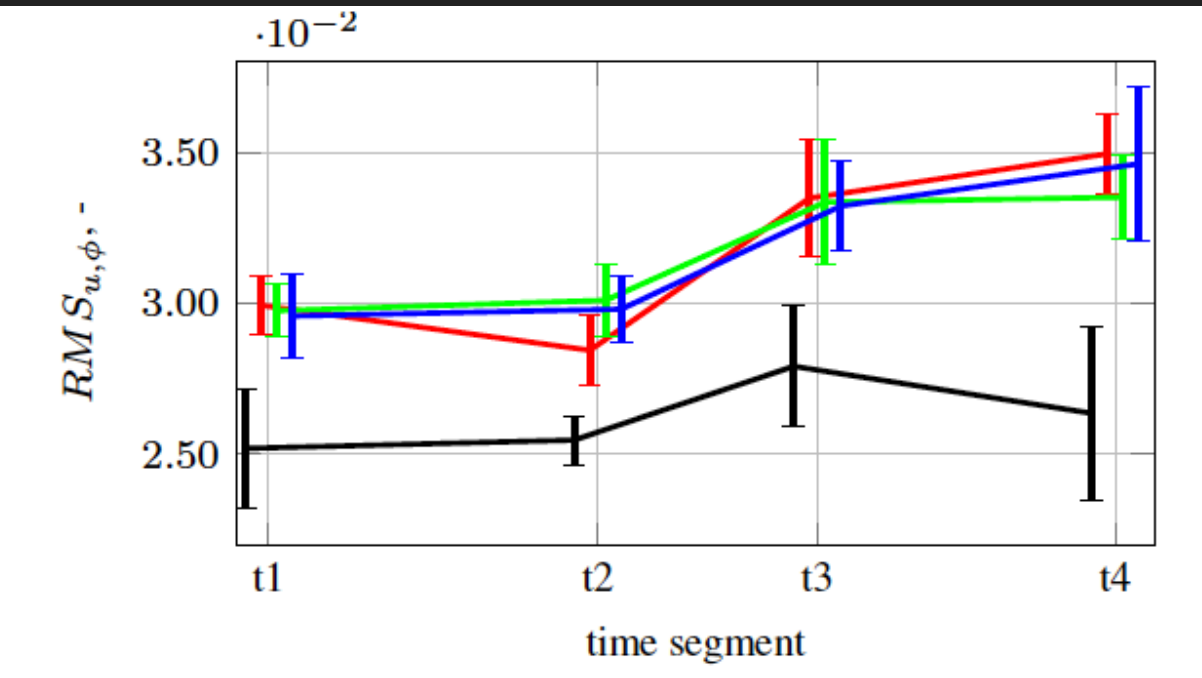
$$K_{s,k} = P_{s,k}^- G_{s,k}^T [G_{s,k} P_{s,k}^- G_{s,k}^T + R]^{-1}$$
$$P_{s,k}^+ = (I - K_{s,k} G_{s,k}) P_{s,k}^- (I - K_{s,k} G_{s,k})^T + K_{s,k} R K_{s,k}^T$$

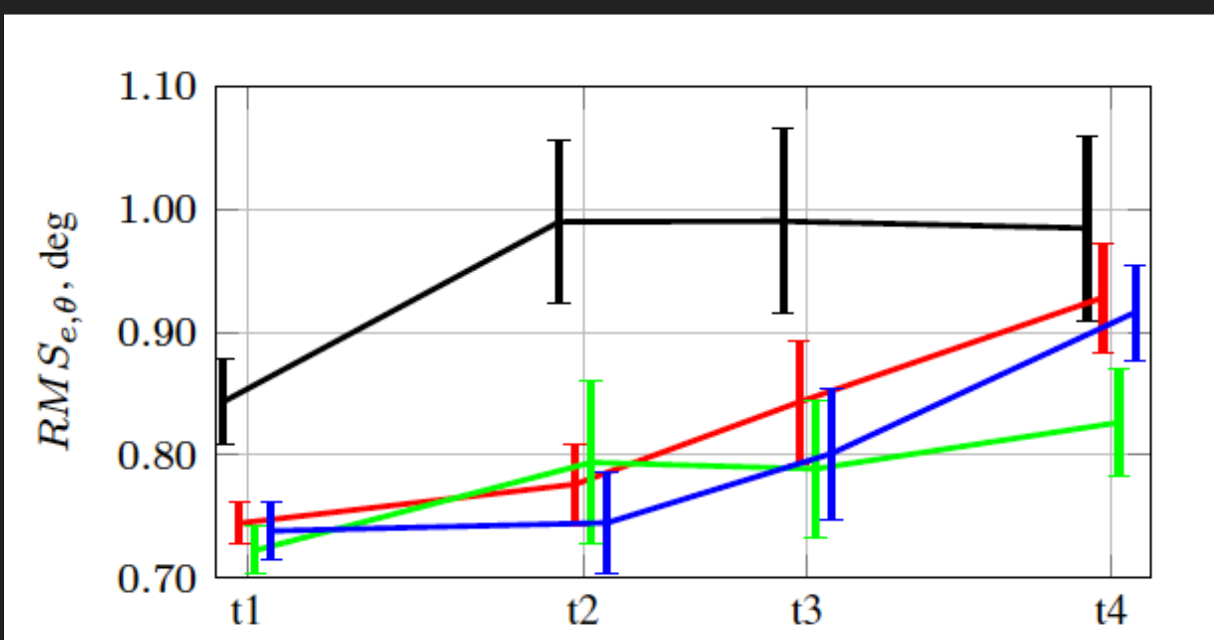
Parameter filter correction:

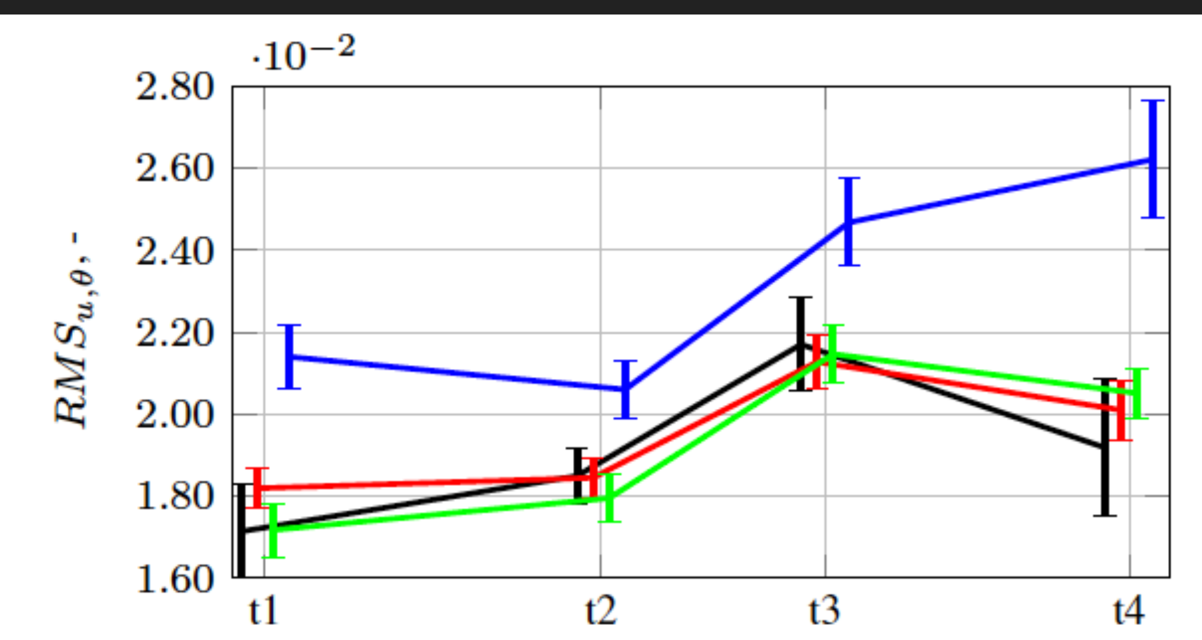
$$K_{p,k} = P_{p,k}^- (G_{p,k}^{tot})^T [G_{p,k}^{tot} P_{p,k}^- (G_{p,k}^{tot})^T + R]^{-1}$$
$$\boldsymbol{\theta}_k^+ = \boldsymbol{\theta}_k^- + K_{p,k}[u_k - g(\boldsymbol{x}_{s,k}^-, e_k, \boldsymbol{\theta}_k^-)]$$
$$P_{p,k}^+ = (I - K_{p,k} G_{p,k}^{tot}) P_{p,k}^- (I - K_{p,k} G_{p,k}^{tot})^T + K_{p,k} R K_{p,k}^T$$

RMS E, U


1.60
1.40
1.20
1.00
0.80
0.60
0.40
$RMS_{e,\phi}$, deg
NM
GH
EH
FM
t1
t2
t3
t4
time segment


$\cdot 10^{-2}$
3.50
3.00
2.50
$RMS_{u,\phi}$, -
t1
t2
t3
t4
time segment


1.10
1.00
0.90
0.80
0.70
$RMS_{e,\theta}$, deg
t1
t2
t3
t4


$\cdot 10^{-2}$
2.80
2.60
2.40
2.20
2.00
1.80
1.60
$RMS_{u,\theta}$, -
t1
t2
t3
t4

FLIGHT CHARACTERISTICS