APISAT 2019

UNMANNED SYSTEMS Ⅵ

Haiyin Piao

Datalink Delay Induced UAV Payload Releasement Error Compensation Based on Forward Estimated Kalman Filter

Zhixiao Sun, Haiyin Piao, Kun Zhang, Yang Sun, Guang Zhan
From
Shenyang Aircraft Design & Research Institute, AVIC
Northwestern Polytechnical University

ENGINEERS AUSTRALIA

ROYAL AERONAUTICAL SOCIETY AUSTRALIAN DIVISION

Introduction

- UAV is typically composed by aircraft, GCS, datalink and pilot.
- “Airplane and pilot separation”
- Flight state-feedback message delivered to GCS after transmission delay
  - Influences the aiming error and Head-Up Display (HUD) symbol
  - Affects the pilot’s payload release command confirming judgment

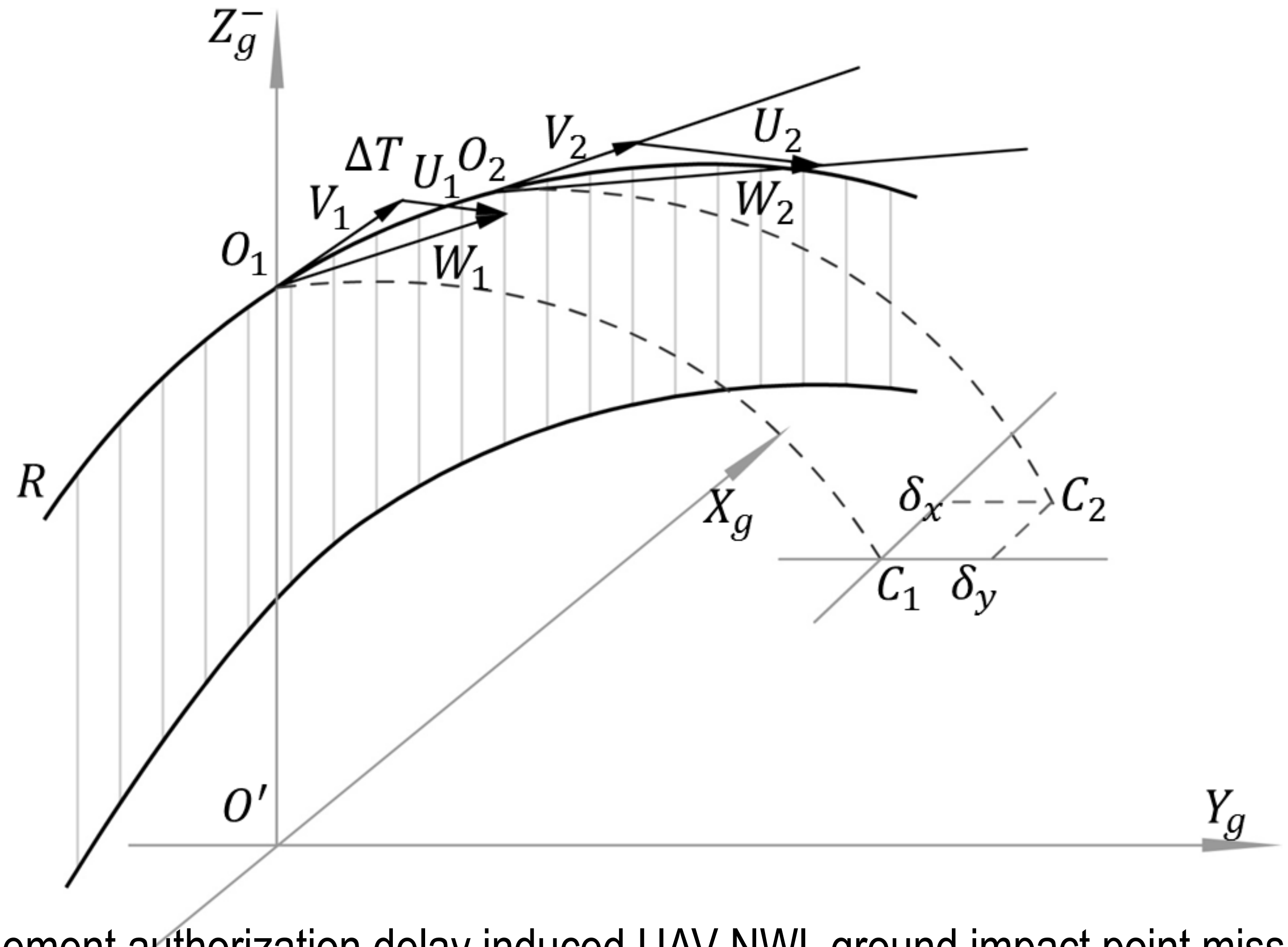
Literature Review

- Hattis and Grisword established the guidance and control dynamics model for aircraft payload releasement[1-2]
- Guo proposed a new predictive filter which could compensate the UAV message transmission delay[3]
- Nagarajan and Jawhar improves the UAV datalink communication performance in perspective of communication and network[4-5]
- Ryo focused on Receding-Horizon Unscented Kalman Filter which was applied in spacecraft attitude estimation[6]
- Jia proposed a sparse gauss-hermite quadrature filter for spacecraft attitude estimation[7]

Problem to Solve

- Current research does not propose an effective compensation or estimation method for the UAV payload releasement error induced by datalink delay and jitter yet
- We proposed Forward Estimation Kalman Filter (FEKF)

Problem Description



Payload releasement authorization delay induced UAV NWL ground impact point miss-distance

Problem Description

- Error caused by ΔT

$$\Delta\chi = \frac{g\sqrt{n_n^2 - 1}}{|\boldsymbol{W}|} \cdot \Delta T$$

$$\boldsymbol{W} = \boldsymbol{V} + \boldsymbol{U}$$

- Need to get compensated

$$\Delta A = 2R\sin \Delta\chi / 2$$

Forward Estimated Kalman Filter (FEKF)

- To reduce the influence of the payload releasement authorization delay induced by datalink communication channel, it is necessary to estimate the actual current state of the UAV.
- For the Linear Time Invariant (LTI) process of UAV lateral NWL payload releasement, Linear Kalman Filter can be used.

Forward Estimated Kalman Filter (FEKF)

$$\boldsymbol{P}_k^- = \boldsymbol{A}\boldsymbol{P}_{k-1}\boldsymbol{A}^T + \boldsymbol{Q}$$

$$\boldsymbol{K}_k = \boldsymbol{P}_k^- \boldsymbol{H}^T \left(\boldsymbol{H}\boldsymbol{P}_k^- \boldsymbol{H}^T + \boldsymbol{R} \right)^{-1}$$

$$\hat{\boldsymbol{x}}_k = \hat{\boldsymbol{x}}_k^- + \boldsymbol{K}_k \left(\boldsymbol{z}_k - \boldsymbol{H} \hat{\boldsymbol{x}}_k^- \right)$$

$$\boldsymbol{P}_k = \left(\boldsymbol{I} - \boldsymbol{K}_k \boldsymbol{H} \right) \boldsymbol{P}_k^-$$

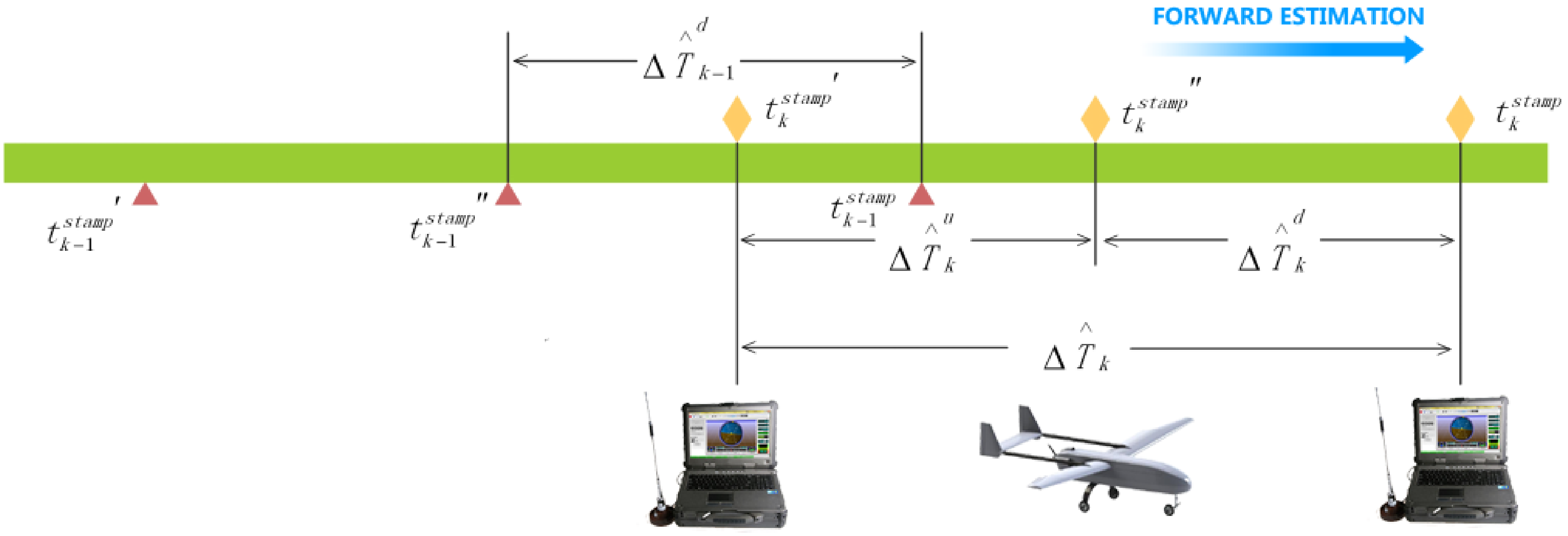
$$\boldsymbol{x} = [x_g, y_g, z_g, \chi, \gamma, \mu]^T$$

- state observation $\boldsymbol{z}_k$ and the prior estimation $\hat{\boldsymbol{x}}_k^-$ can not be obtained directly

Forward Estimated Kalman Filter (FEKF)

- How to get $\hat{\boldsymbol{x}}_k^-$ and $\boldsymbol{z}_k$?

Forward Estimated Kalman Filter (FEKF)



$$\Delta\hat{T}_k^d = \frac{t_k^{stamp} - t_k^{stamp'}}{2}$$

Forward Estimated Kalman Filter (FEKF)

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}$$

$$\dot{\boldsymbol{x}} = \frac{\boldsymbol{x}(t+\Delta T) - \boldsymbol{x}(t)}{\Delta T}$$

$$\frac{\boldsymbol{x}(t+\Delta T) - \boldsymbol{x}(t)}{\Delta T} \cong \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t)$$

$$\boldsymbol{x}(t+\Delta T) \cong \Delta T\boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{x}(t) + \Delta T\boldsymbol{B}\boldsymbol{u}(t)$$
$$\cong (\Delta T\boldsymbol{A} + \boldsymbol{I})\boldsymbol{x}(t) + \Delta T\boldsymbol{B}\boldsymbol{u}(t)$$

$$\hat{\boldsymbol{x}}_k^- = \left(\Delta \hat{T}_k^d \boldsymbol{A} + \boldsymbol{I}\right)\hat{\boldsymbol{x}}_{k-1}$$

$$\boldsymbol{z}_k = \left(\Delta \hat{T}_k^d \boldsymbol{A} + \boldsymbol{I}\right)\boldsymbol{z}_{k-1}$$

- Look $\Delta \hat{T}_k^d$ Forward

- After $\Delta \hat{T}_k^d$ estimated, states can be revealed by Eulerian method

Forward Estimated Kalman Filter (FEKF)

$$\begin{cases} \dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) \\ \boldsymbol{x}\left(t_k^{stamp''}\right) = \boldsymbol{x}_0 \end{cases}, t \in \left[t_k^{stamp''}, t_{k-1}^{stamp}\right]$$

$$\hat{\boldsymbol{x}}_k^- = \boldsymbol{x}\left(t + \Delta\hat{T}_k^d\right) = \boldsymbol{x}(t) + \frac{\Delta\hat{T}_k^d}{6}\left(\boldsymbol{K}_1 + 2\boldsymbol{K}_2 + 2\boldsymbol{K}_3 + \boldsymbol{K}_4\right)$$

$$\boldsymbol{K}_1 = \mathrm{f}\left(t_k^{stamp''}, \boldsymbol{x}\left(t_k^{stamp''}\right)\right)$$

$$\boldsymbol{K}_2 = \mathrm{f}\left(t_k^{stamp''} + \Delta\hat{T}_k^d/2, \boldsymbol{x}\left(t_k^{stamp''}\right) + \Delta\hat{T}_k^d/2 \cdot \boldsymbol{K}_1\right)$$

$$\boldsymbol{K}_3 = \mathrm{f}\left(t_k^{stamp''} + \Delta\hat{T}_k^d/2, \boldsymbol{x}\left(t_k^{stamp''}\right) + \Delta\hat{T}_k^d/2 \cdot \boldsymbol{K}_2\right)$$

$$\boldsymbol{K}_4 = \mathrm{f}\left(t_k^{stamp''} + \Delta\hat{T}_k^d, \boldsymbol{x}\left(t_k^{stamp''}\right) + \Delta\hat{T}_k^d \boldsymbol{K}_3\right)$$

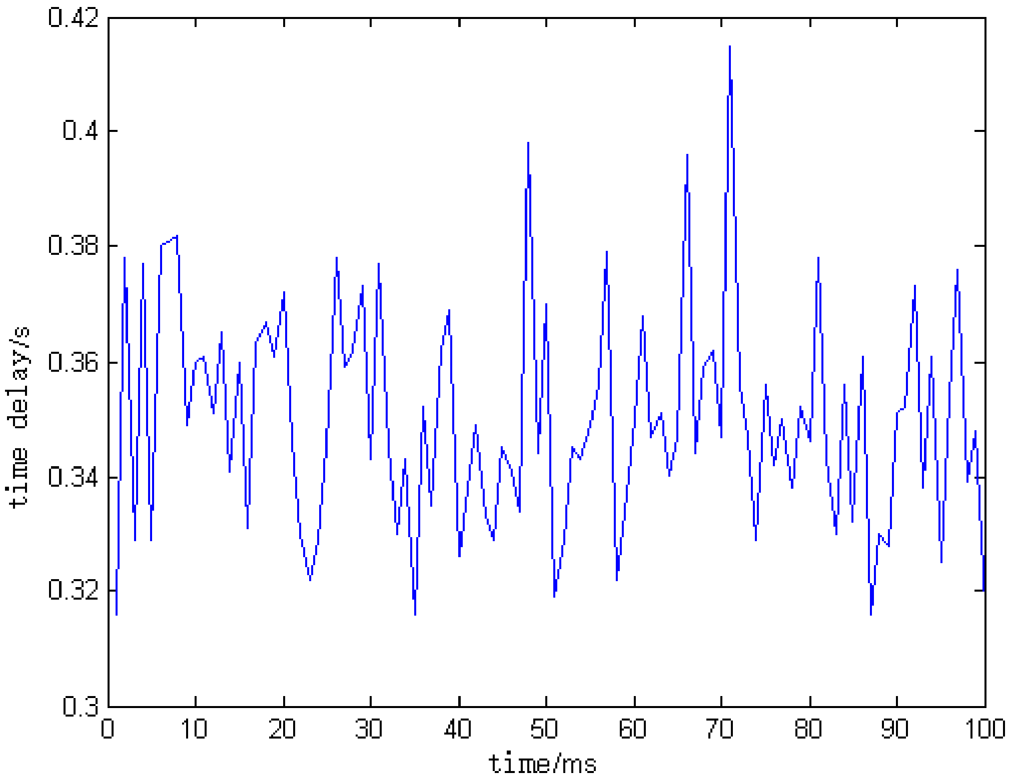
- 4th order Runge-Kutta = **Better Estimation**

Forward Estimated Kalman Filter (FEKF)

- We need simulation to demonstrate our idea.

Simulation System Modeling - Datalink Delay

$$y = f(x|\lambda) = \frac{\lambda^x}{x!} e^{-\lambda} I_{(0,1,\ldots)}(x)$$



Simulation System Modeling - Flight Mechanics

$$
\begin{cases}
\dfrac{dx_g}{dt} = v_{dx} = v\cos\gamma\cos\chi \\
\dfrac{dy_g}{dt} = v_{dy} = v\sin\gamma \\
\dfrac{dz_g}{dt} = v_{dz} = -v\cos\gamma\sin\chi \\
\dfrac{dv}{dt} = -\left[D_0 + D_i(n_D^2 + n_T^2)\right]/m - g\sin\gamma \\
\dfrac{d\gamma}{dt} = g(n_D - \cos\gamma)/v \\
\dfrac{d\chi}{dt} = gn_T/\left(v\cos\gamma\right)
\end{cases}
$$

$$
\vec{\boldsymbol{R}} = \begin{bmatrix} -D \\ L\cos\mu \\ L\sin\mu \end{bmatrix} = \begin{bmatrix} -C_D qS \\ C_L qS\cos\mu + C_c qS\sin\mu \\ C_L qS\sin\mu - C_c qS\cos\mu \end{bmatrix}
$$

Simulation System Modeling - Steering

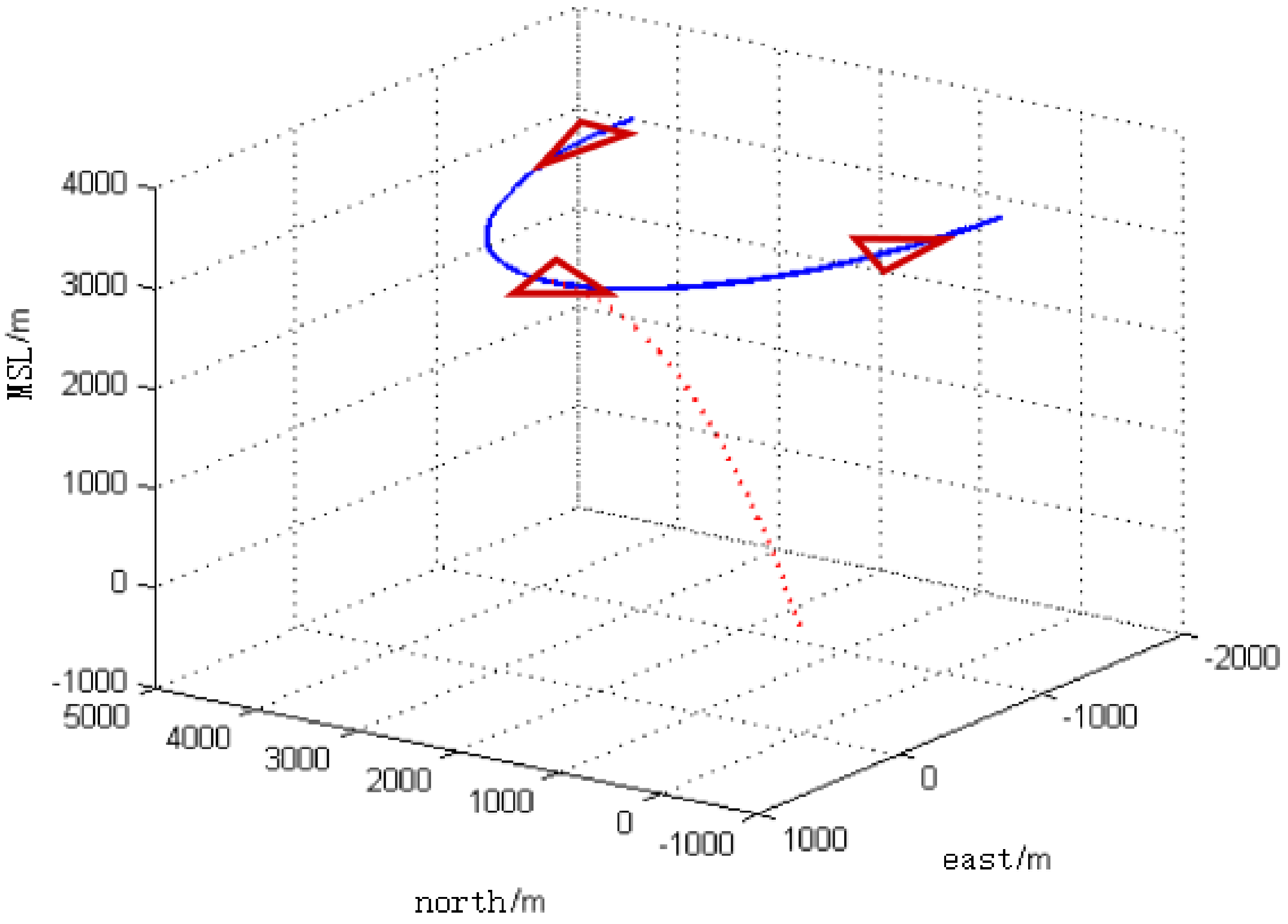
$$A\sin\left(\frac{A_n v}{R_p^2 - A_t^2}\right) - A_n\cos\left(\frac{A_n v}{R_p^2 - A^2}t\right) + A_t\sin\left(\frac{A_n v}{R_p^2 - A^2}t\right) = 0$$

$$A_t = x_i\cos\chi_c + y_i\sin\chi_c - |\boldsymbol{U}|(t+T)\cos(\varepsilon - \chi_c)$$

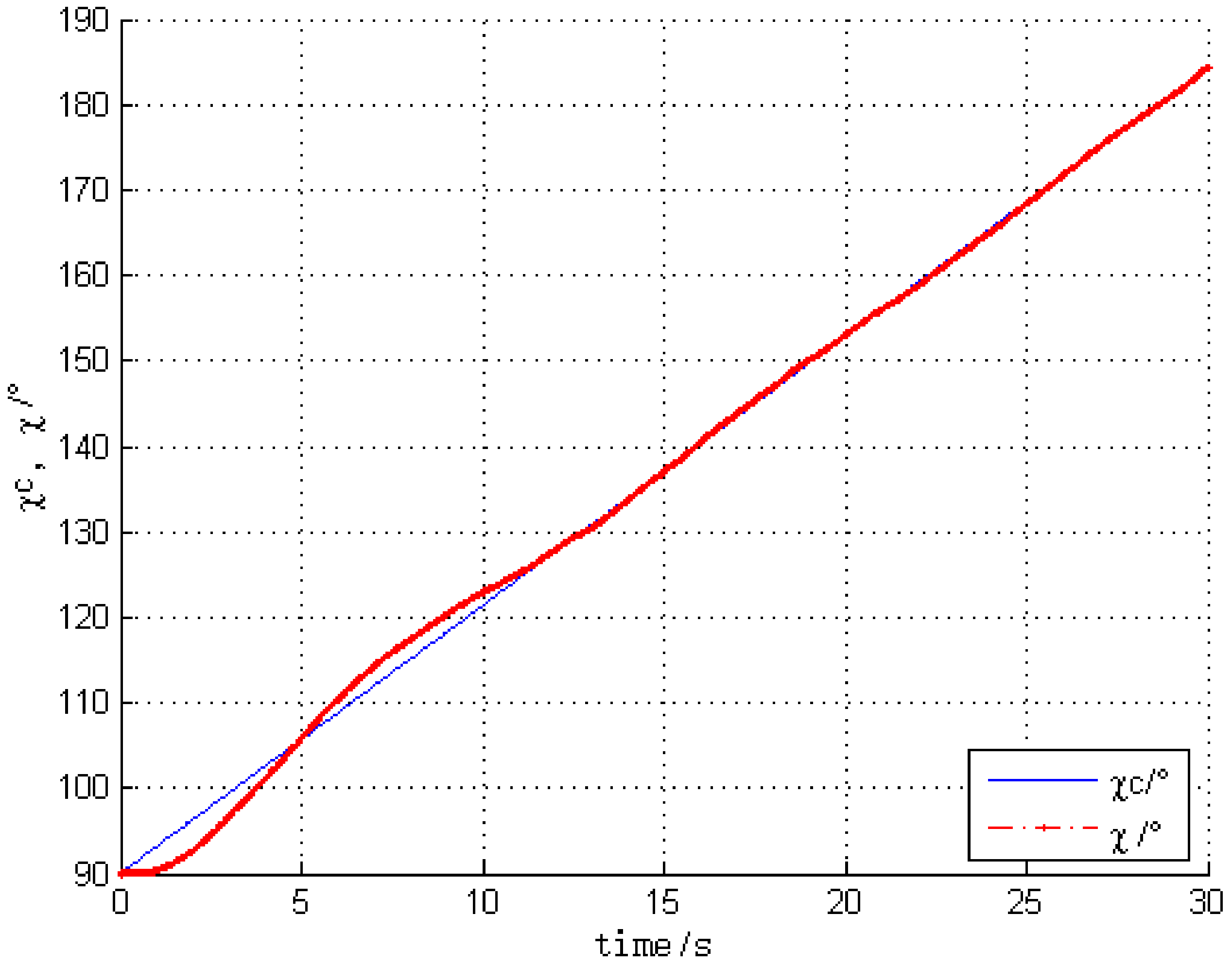
$$A_n = y_i\cos\chi_c + x_i\sin\chi_c - |\boldsymbol{U}|(t+T)\sin(\varepsilon - \chi_c)$$

$$|\boldsymbol{R_p}|^2 = A_t^2 + A_n^2$$

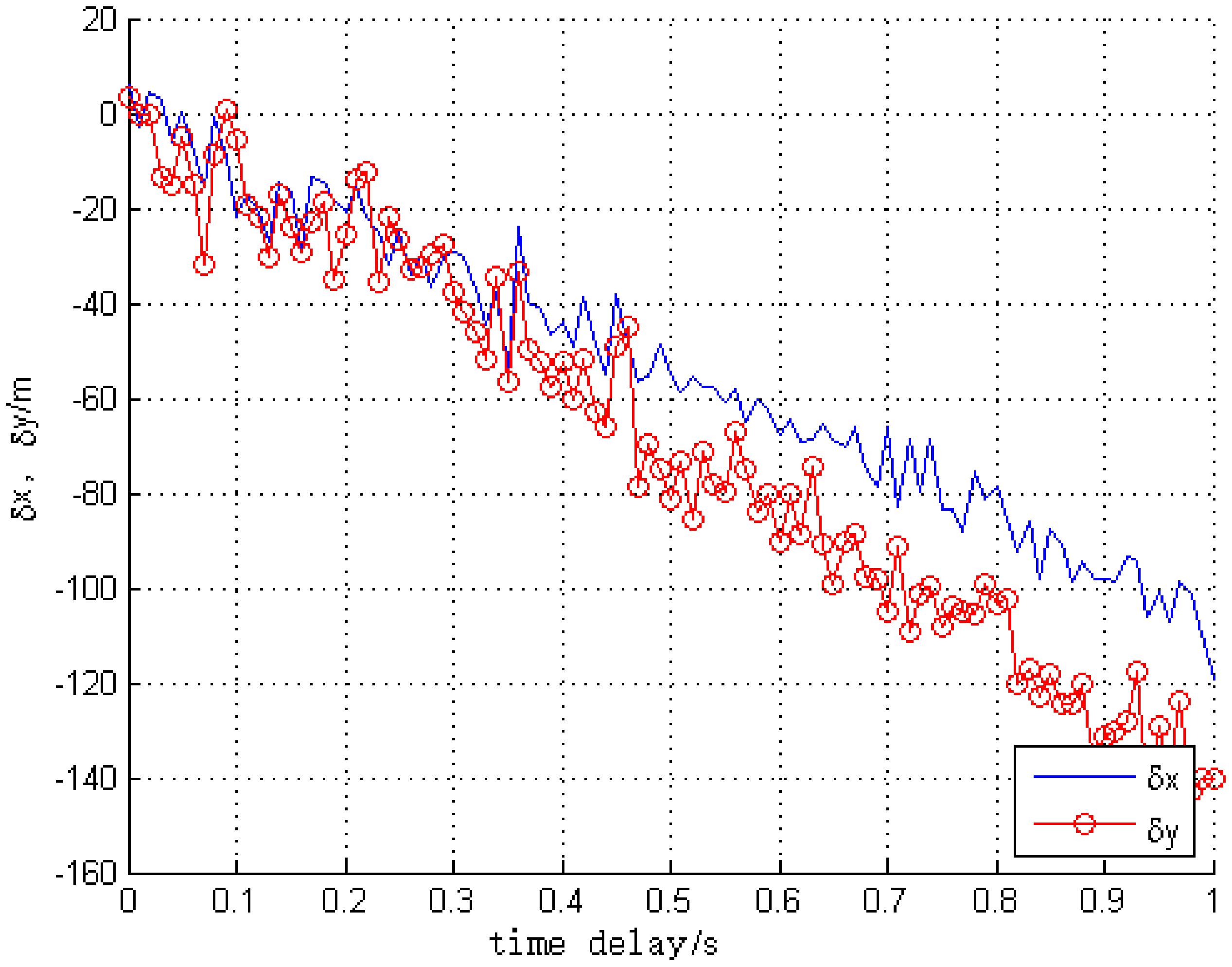
Simulation Result Analysis pre FEKF



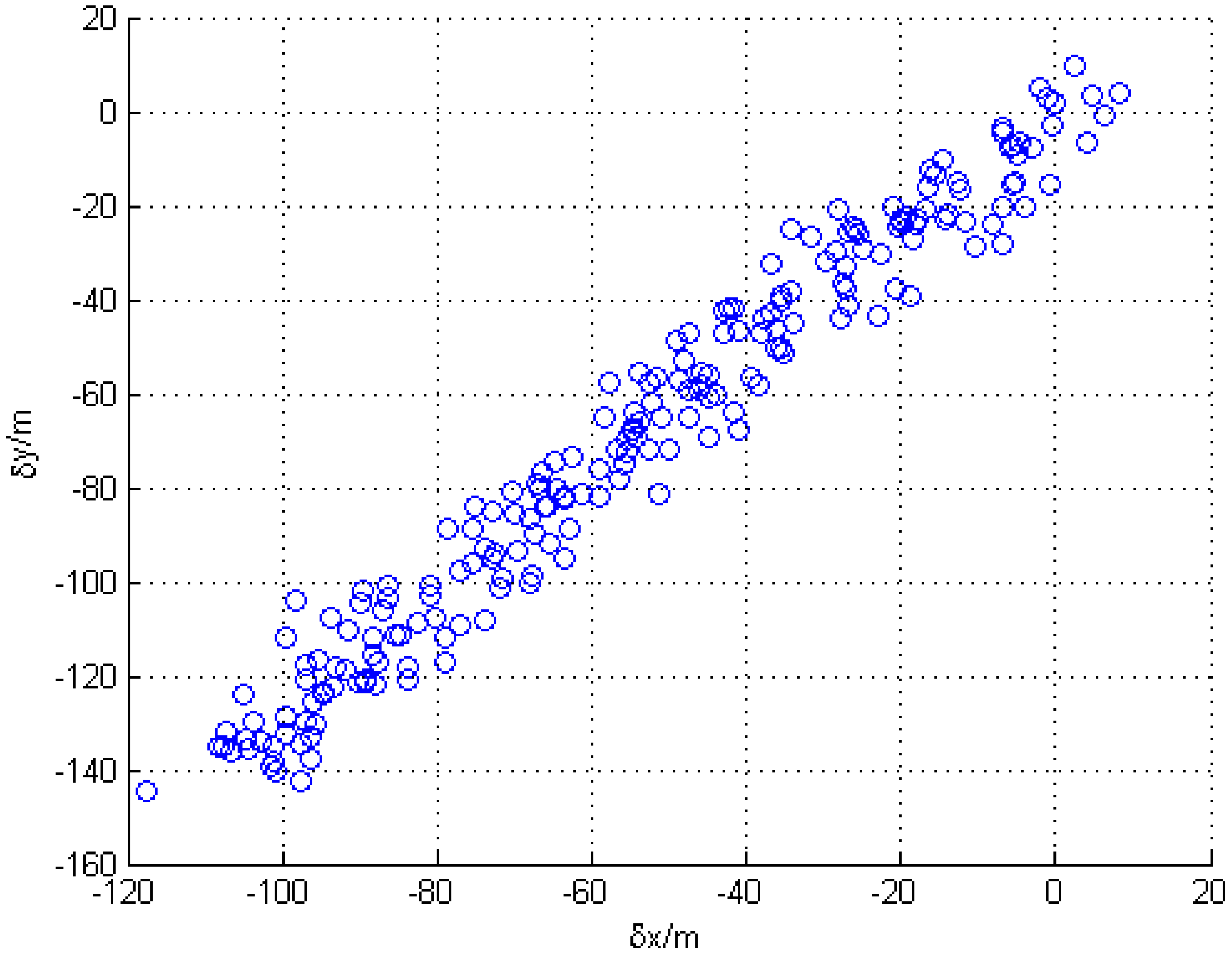
Simulation Result Analysis pre FEKF



Simulation Result Analysis pre FEKF



Simulation Result Analysis pre FEKF



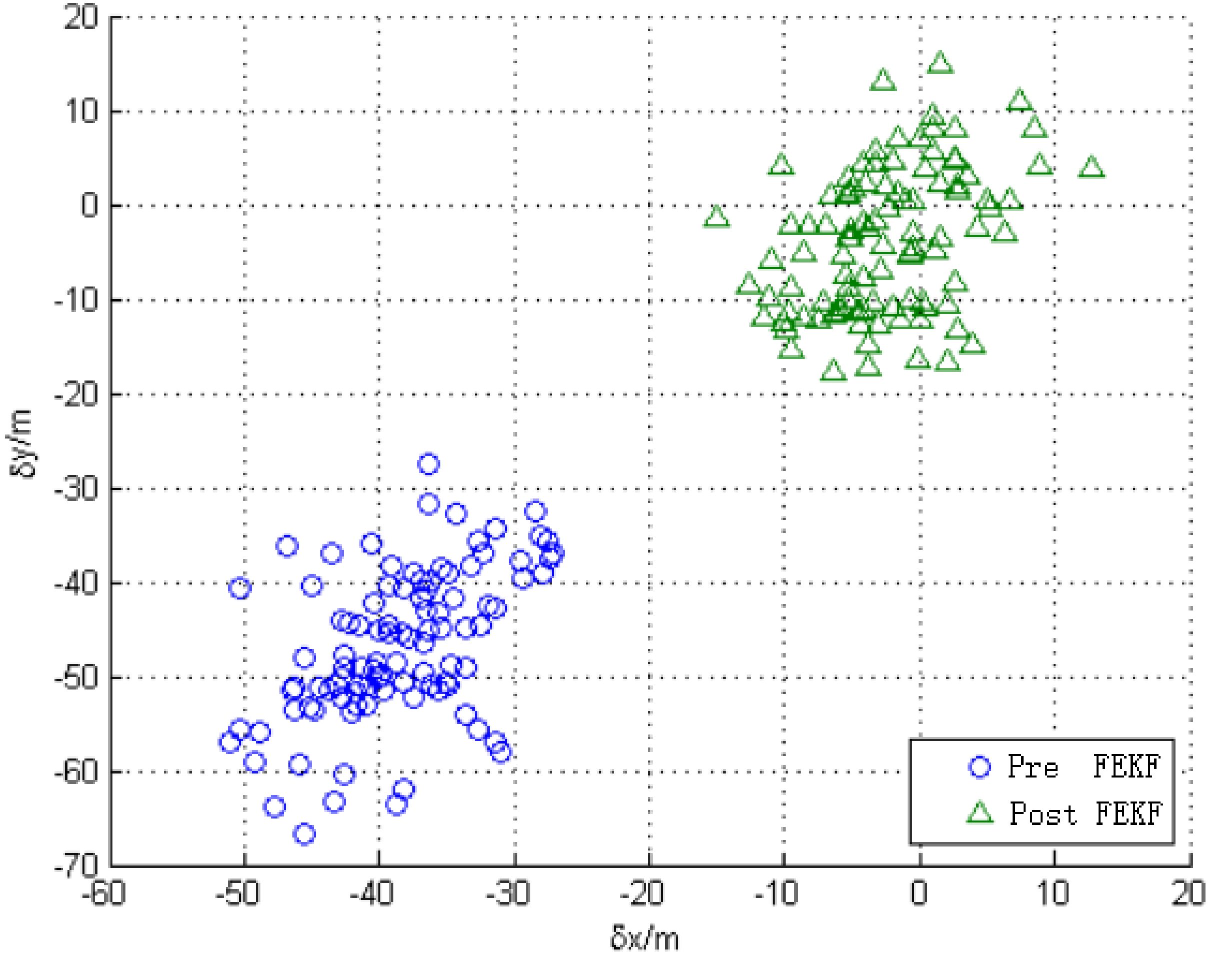
Simulation Result Analysis pre FEKF

Payload impact point miss-distance and RMSE without FEKF

Serial	ΔT/ms	Miss-distance/m	RMSE/m
1	0ms	4.34	5.57
2	100ms	22.34	7.02
3	200ms	32.66	7.76

- Rapidly increasing, not acceptable

Simulation Result Analysis post FEKF



Simulation Result Analysis post FEKF

Payload impact point miss-distance and RMSE without FEKF

Serial	ΔT/ms	Miss-distance/m	RMSE/m
1	0ms	4.21	4.77
2	100ms	3.94	5.02
3	200ms	4.79	4.58

- FEKF = Much Better !

Conclusion

- Forward Estimation Kalman Filter (FEKF)
- Employs a datalink delay forward estimation strategy to predict current state observation and state variable’s prior estimation
- Simulation results revealed that FEKF method could significantly improve the UAV payload releasing miss-distance and RMSE

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Thanks!

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