A Multi-Information Integrated Navigation Method for Shipboard Landing

Y Chen, W Wang, Y Meng and J Y Chen
School of Instrumentation Science and Optoelectronic Engineering,
Beihang University, Beijing, 100191, China
Chenyao17@buaa.edu.cn

Abstract. This paper presents a multi-information integrated landing navigation system for ship landing. It includes satellites, pseudolites, vision and inertial navigation systems. Pseudolites and satellite systems can provide the relative positions between plane and ship, and the vision system can get the relative positions and attitude by identifying targets on the runway. The airborne inertial navigation can provide the aircraft motion information, and the data link can receive the ship motion information. INS is selected as the federated filter reference system, and the satellite, pseudolite, visual and inertial navigation information are fused by the federated filter to Provide navigation information. Through designing simulation experiment by MATLAB. Under the set simulation conditions, the lateral and longitudinal position deviation between the aircraft and the ship is about 0.1m, and the relative vertical position deviation is within 0.3m, which achieve the precision requirement of shipboard landing. The simulation experiment shows that the multi-information integrated navigation method is practicable.

1. Introduction
Carrier-based aircraft are the main combat weapons of aircraft carriers. After years of rapid development in the field of automation technology, taking off and cruise can be automatically accomplished in some situation. But landing remains a challenge, the difficulty is greater than the landing on earth. The reasons are as follows. First of all, the ship area is small, aircraft must be landed in the area with 6 meter wide and 36 meter long to hang arresting cable, A deviation of 1m in height will cause a deviation of 14.3m in the direction of runway. Therefore, if the deviation in height is more than 1.5m, the craft will fail to hook the arresting cable. Furthermore, in order to prepare for the waving off after the failure of hooking arresting cable, the carrier-based aircraft should fly to the deck at the speed of about 240 km/h, so the response time is very short. What’s more, during the glide phase, aircraft should aim at the centerline of the runway, The runway is located on the port side of the carrier, making a 9°3′ angle with the axis of carrier. With the progress of the aircraft carrier, the runway is always moving to the right from the aircraft, thus, aircraft need always aim to the center of runway. Last but not least, affected by waves, the deck of carrier is constantly waving, which makes it difficult to locate the landing point. Above all, The difficulty of landing requires high precision, high reliability, high integrity of the landing navigation system, and the ability to cope with complex weather and severe sea conditions.

Currently, there are many landing navigation systems used at home and abroad, such as Fresnel lens optical aid system, the radar-assisted landing system and the satellite-based landing system[1]. The Fresnel lens optical aid system requires the pilot to observe the Fresnel lens, which is
inconvenient for pilots. In addition, under severe weather conditions, the difficulty in seeing the Fresnel light box increases the risk of landing. The radar-assisted landing system cannot provide lateral and normal speed of aircraft, and is easily interfered by the outside environment, which increases the complexity of electromagnetic management of aircraft carrier. The satellite-based relative positioning system can measure the speed and position of carrier-borne aircraft with extremely high accuracy, but the data update rate is low, cycle slip is easy to occur in dynamic environment, and it is easy to be disturbed [2]. In order to make landing navigation system more efficiently, variously and reliably, it is necessary to make use of the advantages of various technologies. Zheng studied the use of GPS for aircraft precision approach and discussed the accuracy of the system and the differential GPS technology with pseudolite, and the problem of inertial aided information[3].Wang proposed a landing navigation scheme based on GPS/SINS and supplemented by computer vision/SINS[4].Ding studied the infrared/inertial/radar integrated landing navigation technology, the positioning accuracy in the vertical direction was unsatisfied[5].

This paper proposes a satellite/pseudolite/visual/inertial integrated navigation technology, using federated filter to fuse multi-information which have different update frequency and characteristics. The federated filter uses the inertial navigation system as a reference system, and the visual system and satellite-pseudolite systems respectively combined with the inertial navigation information to form two local filters. The local filter consisted of visual system and INS solves the relative position and orientation from the vision information and then taking them as observations of the filter. The other local filter takes the differential pseudorange and carrier phase as observation to solve for relative position. For demonstration, an simulated experiment is designed and the results show that the multi-information integrated landing navigation system achieves satisfied results.

The rest of the paper is organized as follows: Section 2 introduces the frames which are involved in the algorithm, the design of the federal filter and the algorithm of each local filter. In Section 3, the initial condition, result and analysis of simulation are described. Finally, conclusion are drawn in section 5.

2. System design and algorithm

2.1. Definition of frame

The frame $F_S$, $F_R$, $F_{RR}$, $F_B$ and $F_C$ respectively represent the ship body frame, the ship runway frame, the ship runway reference frame, the aircraft body frame and the camera frame. The original point of $F_R$ is the ideal landing point. The difference between the ship runway reference frame and the ship runway frame is that the ship runway reference doesn’t have ship motion. The frames involved are presented in Figure. 1.

![Involved frames](image-url)
2.2. Algorithm theory

2.2.1. Algorithm of satellite navigation. The satellite navigation system has the characteristics that the error changes slowly with time, but it is significantly affected by distance and path. The difference method can eliminate common errors and most propagation delay errors, thus significantly improving the positioning accuracy.

The receiver receives signals including the ephemeris, pseudo-range and carrier phase of all visible satellites. The pseudo-code distance and carrier phase of L1 carrier signal are defined as \( \rho_{\text{PR}L1} \) and \( \phi_{\text{L1}} \) (frequency: 1575.42mhz), and the pseudo-code distance and carrier phase of L2 carrier signal are defined as \( \rho_{\text{PR}L2} \) and \( \phi_{\text{L2}} \) (frequency: 1227.6mhz).

Geometrically independent observation is an estimator of the overall ambiguity of a wide lane [6]:

\[
Z_{\text{GF}}^i = N^i + \epsilon_{\text{GF}} + b
\]

Where \( \epsilon_{\text{GF}} \) and \( b \) are respectively random error and zero deviation error. Meanwhile

\[
Z_{\text{GF}}^i = \phi_{L1} - \phi_{L2} - \frac{f_{L1} - f_{L2}}{c} \cdot \frac{\rho_{\text{PR}L1} \cdot f_{L1} + \rho_{\text{PR}L2} \cdot f_{L2}}{f_{L1} + f_{L2}}
\]

Where \( c \) is speed of light, \( f_{L1} \) and \( f_{L2} \) are respectively carrier frequencies of L1 and L2.

The random error of \( Z_{\text{GF}}^i \) can be reduced through data smoothing:

\[
Z_{\text{GF}i}^i = \frac{1}{M} Z_{\text{GF}}^i + \frac{M-1}{M} Z_{\text{GF}}^i_{i-\Delta t}
\]

Where \( M \) is the pre-filtering time, \( \Delta t \) is the sampling period.

The relative positions of ships and aircraft can be expressed as:

\[
\begin{bmatrix}
\n\n\n\n\end{bmatrix}
\]

Where, \( \nabla \Delta \phi_{\text{SL1,om}} \) and \( \nabla \Delta \phi_{\text{SL2,om}} \) are the dual-differential carrier phase observations of the satellite, \( \lambda_{L1} \) and \( \lambda_{L2} \) are the carrier wavelengths of L1 and L2, \( X \) is the relative position vector between the ship and the aircraft (from the ship to the aircraft), \( I \) is the unit vector, \( \epsilon \) is the phase error of double differential carrier, \( \nabla \Delta N_{\text{SL1,om}} \) and \( \nabla \Delta N_{\text{SL2,om}} \) are the dual-differential integer ambiguity, \( \Delta \epsilon_{\text{SL}} \) are the difference of direction cosine from the host satellite to the slave satellite. The coordinates in the equation(4) are in the agreed earth frame.

2.2.2. Algorithm of pseudolite navigation. Pseudolite has the advantage of strong anti-interference capacity and flexible arrangement, which can enhance the navigation and positioning accuracy of satellite system. Since the distance between pseudolite and the user is too close, the dual-difference pseudolite algorithm is not suitable for pseudolite system, so the single-difference pseudolite algorithm is adopted to solve the problem of pseudolite positioning.

As the distance between pseudolite transmitting stations is very close, the influence of signals propagation in atmospheric can be ignored, and the differential processing eliminates the clock error of the user receiver and avoids the complex problem of modeling caused by the low clock accuracy of the receiver.

The pseudo-distance observation equation of a single pseudo-satellite is:

\[
\rho_i = |r - r_i| + c \times \delta_i + \epsilon_i
\]

The single difference pseudo-distance observation equation is expressed as:

\[
\rho_i - \rho_j = |r - r_i| - |r - r_j| + \delta_i + \epsilon_i - \epsilon_j
\]

Linearized to get:

\[
\Delta \rho_{i,j} - \Delta d_{i,j} = (e_i - e_j) \delta r + \epsilon_i - \epsilon_j
\]
2.2.3. Algorithm of Vision navigation. The camera installed on the carrier aircraft identify the combined targets calibrated on the ship, and the transformation matrix between $F_s$ and $F_c$ can be solved through the coordinates of the combined targets in the image frame and the runway frame. Then, the relative position and attitude of ship and aircraft can be calculated by transfer matrix.

Literature [7] proposed an airbased vision/Radar/INS integrated navigation method based on infrared detection. The airbased vision/inertial integrated navigation system integrates the image information provided by infrared detector with the inertial information provided by airbased INS to provide the information of landing navigation. This paper uses this method to design vision/inertial navigation filter. There are four cooperative targets installed near the carrier landing runway, as shown in figure 2, which are installed at four positions of A, B, C and D to improve the accuracy of landing navigation system.

![Figure 2. The location of targets.](image)

According to the attitude angle of the aircraft relative to the runway frame, the relationship between the coordinate in camera frame and the coordinate in runway frame can be expressed as:

\[
\begin{bmatrix}
    x^c \\
    y^c \\
    z^c
\end{bmatrix} = R_b^c \begin{bmatrix}
    x^b \\
    y^b \\
    z^b
\end{bmatrix} - T^b_c
\]

Where $R_b^c$ is the rotation matrix from the runway frame to the aircraft body frame, and $T^b_c$ is the coordinates of the origin of the runway frame under the aircraft body frame, $R_b^c$ is the rotation matrix from the runway frame to the camera frame.

The transformation relation between camera coordinates system and image frame is:

\[
\begin{bmatrix}
    u \\
    v \\
    w
\end{bmatrix} = \begin{bmatrix}
    f/p_x & 0 & u_0 \\
    0 & f/p_y & v_0 \\
    0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
    X^c \\
    Y^c \\
    Z^c
\end{bmatrix}
\]

Where $f$ is the focus length, $p_x$, $p_y$ is the length of the detection unit.

2.3. Federal filter design

2.3.1. Filter Design. Considering the high precision of each sensor and the high fault tolerance requirement of the system, the federal filter chooses no-reset structure to fuse multi-information[8]. The federated filter is composed of two local filters and one main filter. One of the local filters (LF_A) is composed of satellite, pseudo-satellite and inertial system. The other local filter (LF_B) is composed of vision and inertial system. The block diagram of federal filter is shown in figure 3.
2.3.2. **State equation.** Considering that carrier-based aircraft and carrier are in different medium, affected by waves, wind and other external factors, their relative motion is so complex that it’s necessary to get real-time attitude and relative location data. According to the information required by each algorithm, this paper selects 22-dimensional state variables to describe their relative motion relations. The state variables are chosen as follow:

\[
X = \begin{bmatrix}
    p_b^R, v_b^R, a_b^R, \Omega_b^R, \Omega_b^R, M_S^R, M_S^R, \delta_j
\end{bmatrix}
\]  

(11)

where \(p_b^R, v_b^R, a_b^R\) are the position, speed and acceleration of carrier-based aircraft, \(\Omega_b^R, \Omega_b^R\) are the attitude angle and angular velocity of carrier-based aircraft, \(M_S^R, M_S^R\) are the pitch, roll, rise and fall of the ship movement and the corresponding angular velocity, \(\delta_j\) is the clock error of pseudolite.

The model for state equation of discretization is expressed as:

\[
X_j(k) = \Phi_j(k / k - I)X_j(k - I) + U_j(k - I) + W_j(k - I)
\]

(12)

Since the carrier aircraft needs to fly along the ideal glide line at a constant speed during landing, the non-zero mean time correlation model is suitable for this situation. The random maneuvering acceleration of the aircraft fits the first-order Markov process in time\([9]\), which can be expressed as:

\[
\dot{x}(t) = \bar{a}(t) + \delta a(t), \quad \dot{\delta} a(t) = -\frac{1}{\tau} \delta a(t) + w
\]

(13)

Where, \(\bar{a}(t)\) is the current mean value of maneuvering acceleration, and \(\delta a(t)\) is the random maneuvering acceleration, which can deduce:

\[
\bar{x}(t) = -\frac{1}{\tau} \bar{x}(t) + \frac{1}{\tau} \bar{a}(t) + w(t)
\]

(14)

where \(\tau\) is time constant, and \(w(t)\) is Gaussian noise.

For linear motion, the state transition matrix is

\[
\Phi_{x}(k / k - 1) = \begin{bmatrix}
    I_{3x3} & T \cdot I_{3x3} & (I - \frac{T}{\tau_0}) \tau_0 I_{3x3} & (1 - \frac{T}{\tau_0}) \tau_0 I_{3x3} & (1 - \frac{T}{\tau_1}) \tau_1 I_{3x3} & (1 - \frac{T}{\tau_1}) \tau_1 I_{3x3}
\end{bmatrix}
\]

(15)

The system noise vector is \(W_i = \begin{bmatrix} 0 \alpha, w_{ax}, w_{ay}, w_{aw} \end{bmatrix}^T\). And the input vector is

\[
U_i = \begin{bmatrix}
    0 \alpha, \bar{a}_x, \bar{a}_y, \bar{a}_w
\end{bmatrix}^T
\]

(16)

For the attitude of aircraft, the state transition matrix is
\[
A_2 = \begin{bmatrix}
\cos \gamma_0^\theta & 0 & \sin \gamma_0^\theta \\
-\sin \gamma_0^\theta \tan \theta_0^\theta & 1 & -\cos \gamma_0^\theta \tan \theta_0^\theta \\
-\sin \gamma_0^\theta / \cos \theta_0^\theta & 0 & \cos \gamma_0^\theta / \cos \theta_0^\theta
\end{bmatrix}
\]  
(17)

\[
\Phi_{2,k+1} = I + A_2 T + \frac{(A_2 T)^2}{2} + \frac{(A_2 T)^3}{3!} + \ldots
\]  
(18)

The system noise vector is
\[
U_2 = \begin{bmatrix}
\xi_1 \\
\xi_2 \\
\xi_3 \\
\xi_4 \\
\xi_5
\end{bmatrix}
\]
And the input vector is
\[
U_2 = \begin{bmatrix}
\xi_1 \\
\eta_1 \\
\eta_2 \\
\eta_3 \\
\eta_4
\end{bmatrix}
\]

2.3.3. Observation equation. The observations of the LF_A include two parts. The image coordinates of targets collected by the camera: 
\[
Z_2 = \begin{bmatrix}
u_1' \\
u_2' \\
u_3' \\
\cdots \\
u_n'
\end{bmatrix}
\]
Attitude information measured by onboard inertial navigation system: 
\[
Z_2 = \begin{bmatrix}
\theta_s \\
\gamma_s \\
\omega_\theta \\
\omega_\gamma \\
\omega_\omega
\end{bmatrix}
\]
, and 
\[
Z_{LF_A} = [Z_1 : Z_2]
\]

The extended kalman filter is adopted to complete the design of vision/INS sub-filter, and the detailed design of observation equation can be referred to in reference [7].

The observations of the local filter B include four parts: The double differential pseudorange of satellite system: 
\[
Z_3 = \begin{bmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{bmatrix}
\]
, The differential pseudorange of pseudolite system: 
\[
Z_4 = \begin{bmatrix}
\xi_1 \\
\xi_2 \\
\xi_3
\end{bmatrix}
\]
, The ship motion and Relative course Angle: 
\[
Z_5 = \begin{bmatrix}
\theta_s \\
\gamma_s \\
\omega_\theta \\
\omega_\gamma \\
\omega_\omega
\end{bmatrix}
\]

The observation equation is:
\[
Z_{LF_B} = \begin{bmatrix}
O_{(n-1)x} \\
O_{(n-1)y} \\
O_{(n-1)z} \\
O_{(n-1)\gamma} \\
O_{(n-1)x} \\
O_{(n-1)y} \\
O_{(n-1)z} \\
O_{(n-1)\gamma}
\end{bmatrix} X + V_{LF_B}
\]  
(20)

Where \( \nabla \Delta e \) is the double difference of direction cosine of the satellites, \( \nabla e \) is the difference of direction cosine of the pseudolites.

2.3.4. Master filter design. In the no-reset federated filter, the filter does not allocate information, so the master filter only performs status updates and information fusion. The equations are as follows:
\[
P_f(k) = \sum_{i=1}^{m} P_i^{-1}(k)
\]  
(21)
\[
\hat{X}_f(k) = P_f(k) \sum_{i=1}^{m} P_i^{-1}(k) \hat{X}_i(k)
\]  
(22)

where \( \hat{X}_f \) and \( P_f \) means the state and covariance matrix of MF from the time update.

The main filter and local filters do not affect each other:
\[
\begin{align*}
\dot{X}_i(k+1/k) & = \Phi_i(k+1,k)\dot{X}_i(k), \quad (i = 1, 2, m) \\
\hat{P}(k+1/k) & = \Phi_i(k+1,k)\hat{P}(k)\Phi_i^T(k+1,k) \\
 & + \Gamma(k+1,k)Q(k)\Gamma^T(k+1,k)
\end{align*}
\]

The MF doesn’t have observations update:
\[
\begin{align*}
\hat{P}_i^{-1}(k) & = \hat{P}_i^{-1}(k/k-I) + H_i^T(k)R_i^{-1}(k)H_i(k), \quad (i = 1, 2) \\
\hat{P}_i^{-1}(k)\hat{X}_i(k) & = \hat{P}_i^{-1}(k/k-I)\hat{X}_i(k/k-I) \\
 & + H_i^T(k)R_i^{-1}(k)Z_i(k)
\end{align*}
\]

3. Simulation

3.1. Initial condition. A simulation is accomplished by using MATLAB. A ship sails to east at the speed of 20knots. An aircraft firstly levelled out at 400m, then glide down to the runway at the angle of 4 degree. Simulation time was 110s.

The clock error of satellite and pseudolite are 1µs, Ionospheric delay is 2.3m, Tropospheric delay is 2m, Receiver pseudo-range measurement error is 1.5m and carrier phase measurement error is 5% of wavelength. The resolution of the vision system is 640×512 pixels. And its view angle is 13.75°×11°. The maximum error in extraction of image coordinates of four targets is 2 pixels. Gyroscope has constant error of 0.01°/h and random noise of 0.01°/h, accelerometer measurement has constant error of 50 µg and random noise of 50 µg. Considering the flying time before landing. The initial error of inertial navigation is position 0.5~0.8hl, velocity 0.5m/s, attitude Angle 1°, course Angle 3°. The output frequencies of the vision system, INS and radar are 25Hz, 100Hz and 10Hz respectively.

3.2. Simulation result and analysis. Considering the long-distance imaging quality of infrared camera is unsatisfactory, the LF_A starts to work at a distance of 2km from the ship, and the simulation result is shown in figure 4(a), which is the estimation error of heading angle, lateral deviation, longitudinal deviation and vertical deviation of carrier-based aircraft, figure 4(b) shows the estimation result of form federal filter.

![Figure 4](image_url)

(a) The estimation errors from LF_B (b) The estimation errors of ship motion
Figure 4 shows When the LF_A doesn’t work, the lateral deviation and height deviation are within 3m. After the LF_A start work at 2km, the lateral deviation and height deviation of the system are significantly reduced. The heading angle deviation and longitudinal deviation have no significant difference before and after the LF_A works.

The data of relative position deviation after 1.5km were selected for analysis. The mean square error of the local filter and the federated filter are obtained through repeated experiments.

| Table 1. Mean Square Error of 5 Experiments (after 1.5km) |
|--------------------------------------------------------|
| LF_B(Satellite/pseudolite/INS) | 0.2689 | 0.1166 | 0.4939 |
| LF_A(vision/INS) | 0.1845 | 1.0193 | 0.1731 |
| Federal Filter | 0.0910 | 0.1226 | 0.2387 |

It can be seen that the lateral deviation of the combined navigation system is about 0.1m, the longitudinal deviation is about 0.1m, and the vertical deviation is within 0.3m. By comparing the errors, it can be seen that the federated filter integrates the advantages of each local filter, The precision meets the needs of ship landing navigation.

On the basis of the above simulation, this paper simulated the system fault. During this period of 100-103s, the infrared camera was selected to simulate the vibration around the X-axis direction of the craft frame, and the shaking was conducted in the form of simulation: \( \theta = 0.5^\circ + 0.5^\circ \sin\left(100\pi t\right) \). The simulation results are shown in the figure 5:

Figure 5. (a) The estimation errors from LF_B when the infrared camera is shaking.
(b) The estimation errors from federal filter when the infrared camera is shaking.

Figure 5(a) shows that the longitudinal error of LF_B is more than 100 m, the data of LF_B can no longer be used to navigate, the federal filter filter has remained at a high precision result, heading angle error is within 0.1 °, lateral deviation is within 1 m, vertical deviation is within 0.5 m. The results show that the federal filter ensures the normal work of the the navigation system.
4. Conclusion
This paper presents a multi-information integrated navigation method for shipboard landing. According to the characteristics of each information and the requirements of the system, we choose the no-reset structure federal filter to fuse the information from multi-system. The system has high fault tolerance and can work normally even when a single local filter fails. Through designing simulation experiment by MATLAB. Under the set simulation conditions, the lateral and longitudinal positions deviation between the aircraft and the ship is about 0.1m, and the relative vertical position deviation is within 0.3m, which achieve the precision requirement of shipboard landing, which achieve the precision requirement of shipboard landing.

References
[1] Lu K., Wang Z. Z, & Yuan S. Z. (2014, August). Automatic landing on carrier method of unmanned air vehicle. In Proceedings of 2014 IEEE Chinese Guidance, Navigation and Control Conference (pp. 299-302). IEEE.
[2] HUANG, S., & ZHONG, X. (2014). Prospect of Automatic Carrier Landing System. Modern Navigation, (1), 17.
[3] Zheng, E. (1991). The feasibility of using GPS/INS for aircraft precision approach landing. Journal of inertial technology, 4(2): 16-23.
[4] Wang W, Wang D. (2011). Research on the algorithm of airborne electro-optical/inertial integrated navigation algorithm. Journal of instrumentation, 32(6): 1311-1316.
[5] Ding, Z., Li, K., Meng, Y., & Wang, L. (2015). FLIR/INS/RA integrated landing guidance for landing on aircraft carrier. International Journal of Advanced Robotic Systems, 12(5), 60.
[6] Lu, K., Li, Q., & Chen, N., (2014, August). An autonomous carrier landing system design and simulation for unmanned aerial vehicle. In Proceedings of 2014 IEEE Chinese Guidance, Navigation and Control Conference (pp. 1352-1356). IEEE.
[7] Meng, Y., Wang, W., Han, H., & Ban, J. (2019). A visual/inertial integrated landing guidance method for UAV landing on the ship. Aerospace Science and Technology, 85, 474-480.
[8] N.A. Carlson. (1990). “Federated square root filter for decentralized parallel processors,” IEEE Transactions on Aerospace and Electronic Systems, vol. 26, no. 3, pp. 517–525.
[9] Qi, Q., et al. (2014). Improved current statistical model algorithm for maneuvering target tracking. Aerospace Shanghai, 31(183), 52-56.
[10] Crassidis, J. L., Mook, D. J., & McGrath, J. M. (1993). Automatic carrier landing system utilizing aircraft sensors. Journal of guidance, control, and dynamics, 16(5), 914-921.
[11] Yakimenko, O. A., Kaminer, I. I., Lentz, W. J., & Ghyzel, P. A. (2002). Unmanned aircraft navigation for shipboard landing using infrared vision. IEEE Transactions on Aerospace and Electronic Systems, 38(4), 1181-1200.
[12] Carlson, N. A. (1990). Federated square root filter for decentralized parallel processors. IEEE Transactions on Aerospace and Electronic Systems, 26(3), 517-525.
[13] Qing, Q., Chengcheng, L., Weilong, G., & Yunze, C. (2014). Improved current statistical model algorithm for maneuvering target tracking. Aerospace Shanghai, 31(183), 52-56.
[14] WANG, W., GUO, H., & MENG, Y. (2017). Satellite/Pseudolite/INS Integrated Navigation Algorithm. Systems Engineering and Electronics, 39, 391-397.
[15] Urnes, J. M., & Hess, R. K. (1985). Development of the F/A-18A automatic carrier landing system. Journal of Guidance, Control, and Dynamics, 8(3), 289-295.