Jamming Research of the UAV GPS/INS Integrated Navigation System Based on Trajectory Cheating

Chang Li
College of Information and Electrical Engineering
Nanjing University of Aeronautics and Astronautic
Nanjing, China

Xudong Wang
College of Information and Electrical Engineering
Nanjing University of Aeronautics and Astronautic
Nanjing, China

Abstract—**Based on the analysis of GPS deception jamming theory, this paper considers the control feathers of the UAV GPS/INS integrated navigation system and designs an innovation detection rule for the UAV navigation system state estimation. Methods of direct track deception and track fusion are used to achieve the intrusive control of the navigation system and the control of the UAV's trajectory through the GPS deception jamming. The normalized innovation squared under two control modes is given through theoretical derivation and simulation analysis. The results show that the method of track fusion not only can realize the cheating of UAV trajectory, but also not easy to be checked, which provides an effective means of interference for GPS countermeasures.**

Keywords—GPS deception jamming; UAV; navigation system; trajectory cheating

I. INTRODUCTION

The UAV navigation system is mainly based on the inertial measurement unit (IMU) and GPS receiver [1]. The inertial system has advantages of concealment, independence and anti-interference [2], GPS has advantages of all positions, all-weather, all time and high precision, but it is vulnerable to be interfered [3]. The conventional GPS deception jamming works mainly through adding time delay to the original satellite signal to change the GPS receiver's positioning results [4], which may cause the jump of positioning results. The UAV with the GPS/INS integrated navigation system will detect interference and discard the GPS measurements as a correction of the positioning results, which will lead to a failure of GPS deception jamming [5].

This paper studies control methods of the UAV navigation system to guarantee the concealment of GPS deception jamming. The radar can be used to get the UAV's position and velocity [6] [7]. So that the time delay and the Doppler shift of each satellite can be calculated. After that, the deceptive signal which is consistent with the real GPS signal needs to be generated to get control of the UAV in the GPS receiver tracking loop. Also, the state estimator of the target UAV needs to be conquered to dominate the UAV inertial navigation system. When the UAV is in a state of flight, it often uses GPS measurements to fix interference [8] [9], so the jammer has an approach to controlling the state estimator. This paper adopts both direct interference and track fusion method to control the navigation system, the simulation results show that track fusion accords with the requirement of concealment, which controls the UAV navigation system and realize the trajectory deception.

II. GPS DECEPTION JAMMING THEORY

A. The Concept of Position Cheating

The GPS receiver uses pseudorange to get position, which needs 4 or more satellite signals. According to the time from each satellite signal transferred to the receiver, distance can be calculated [10].

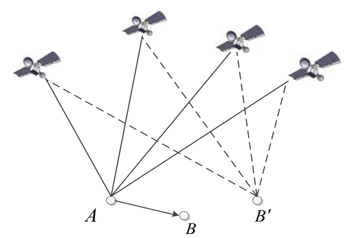

Fig. 1 Schematic of GPS deception jamming

In Fig. 1, A is the jammer and B is the target UAV. After A receives the real satellite signals, according to the relative position of A and B and the expected false position B', each satellite delay can be calculated and the signals will be amplified before A sends them to B. So that B will get a wrong location. Let the coordinates of A, B and B' be (x_A, y_A, z_A), (x_B, y_B, z_B) and $(x_{B'}, y_{B'}, z_{B'})$ respectively, the i th satellite's coordinates be (x_i, y_i, z_i), so the pseudorange [11] between A and i can be expressed as:

$$P_i^A = \sqrt{(x_i - x_A)^2 + (y_i - y_A)^2 + (y_i - y_A)^2} + c(\mathrm{d}t_i - \mathrm{d}t_A) + T_i + I_i \tag{1}$$

In formula (1), $\mathrm{d}t_i$ and $\mathrm{d}t_A$ are the satellite clock offset and jammer clock offset, T_i is the troposphere delay and I_i is the ionospheric delay. The pseudoranges between i and B, i and B' can be expressed as:

$$P_i^B = \sqrt{(x_i - x_B)^2 + (y_i - y_B)^2 + (y_i - y_B)^2} + c(\mathrm{d}t_i - \mathrm{d}t_B) + T_i + I_i \tag{2}$$

$$P_i^{B'} = \sqrt{(x_i - x_{B'})^2 + (y_i - y_{B'})^2 + (y_i - y_{B'})^2} + c(\mathrm{d}t_i - \mathrm{d}t_{B'}) + T_i + I_i \tag{3}$$

According to the principle of GPS pseudorange positioning, the change of pseudorange can make the GPS receiver get the wrong location. To make *B* locate at B', considering $\mathrm{d}t_B$ and $\mathrm{d}t_{B'}$ are the common errors that will not effect the results, the delay of each satellite signal forwarded through *A* to *B* is:

$$\Delta t_i = (P_i^B - P_i^{B'} - P_{AB}) / c \tag{4}$$

In formula 4, P_{AB} is the geometric distance between *A* and *B*. Since the time delay must be positive, let $t_p = \max(\Delta t_i)$, the final time delay of each satellite signal is $\Delta t_i = \Delta t_i + t_p$.

B. The Concept of Velocity Cheating

Besides the spoof of location, the spoof of velocity is also taken into consideration [12]. The carrier phase of real signal and deception signal are ϕ and ϕ_s respectively, so the velocity deviation before and after jamming mapped to the Doppler frequency shift can be expressed as:

$$\Delta f_D \triangleq (\phi - \phi_s) / 2\pi \tag{5}$$

Assume the velocity of the *i* th satellite is (v_x^i, v_y^i, v_z^i), the jammer *A* is static. The direction cosines from *A* to satellite are:

$$\begin{aligned} e_{ix} &= (x_i - x_A) / r_{iA} \\ e_{iy} &= (y_i - y_A) / r_{iA} \\ e_{iz} &= (z_i - z_A) / r_{iA} \end{aligned} \tag{6}$$

In formula (6), r_{iA} is the geometrical distance between *A* and *i*. Since *A* adopts the high precision clock, the effect of clock drift can be ignored. The Doppler frequency of *A* is:

$$f_D^{Ai} = [e_{ix}\ e_{iy}\ e_{iz}] \begin{bmatrix} v_x^i \\ v_y^i \\ v_z^i \end{bmatrix} - df^i \tag{7}$$

Assume the UAV position and velocity tracked by radar are (x_B, y_B, z_B), (v_{Bx}, v_{By}, v_{Bz}), the expected variation of velocity is $(\Delta v_x, \Delta v_y, \Delta v_z)$, so the Doppler frequency of false position B' related to satellite is:

$$f_D^{B'i} = [e_{ix}'\ e_{iy}'\ e_{iz}'] \begin{bmatrix} v_x^i - (v_{Bx} + \Delta v_x) \\ v_y^i - (v_{By} + \Delta v_y) \\ v_z^i - (v_{Bz} + \Delta v_z) \end{bmatrix} - df^i \tag{8}$$

The Doppler frequency of *A* needed to be adjusted is:

$$\Delta f_D = f_D^{B'i} - f_D^{Ai} \tag{9}$$

Compare formula (9) with formula (5), the change of carrier phase can be computed, so that the spoof of velocity is completed.

III. Control of UAV Navigation System

The adjustment of deception signal can make it consistent with the real signal, which can control the track loop of the UAV GPS receiver [13]. Next needed to do is taking control of the UAV navigation system under the tracking loop update interval and limited bandwidth.

The systems of UAV and jammer mainly consist of controller and state estimator. Both of them adopt PD compensator as controller. The estimator of UAV uses VD-Kalman filtering algorithm [14] to track the fight path, the jammer adopts Kalman filtering algorithm under the second order Bayes estimators to track the position and the velocity of UAV. The overall diagram of the design is shown as Fig.2:

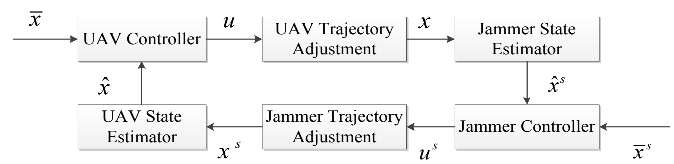

Fig. 2 Overall diagram of the design

In Fig. 2, $\bar{x} = [\bar{p}, \bar{v}, \bar{a}]$, that includes the position $\bar{p}$, velocity $\bar{v}$ and acceleration $\bar{a}$, $\bar{x}$ represents the reference trajectory. $\hat{x} = [\hat{p}, \hat{v}]$, it is the output of UAV state estimator. The output of UAV controller is $u = -K^u(\hat{p}' - \bar{p}')$, $\hat{p}'$ and $\bar{p}'$ are the variation of position estimate and pre-value in unit time T respectively. The dynamic module of UAV trajectory adjustment is $p = \hat{p} + \frac{1}{2}uT^2$, $v = \hat{v} + uT$, $a = u$. The final output of UAV navigation system is x. $\bar{x}^s = [\bar{p}^s, \bar{v}^s, \bar{a}^s]$, which represents the reference trajectory of jammer. The jammer gets the state estimate value x of UAV from the radar, the output of jammer state estimator is $\hat{x}^s$. The output of jammer controller is $u^s = \hat{a}^s + K^s(\hat{p}^s{}' - \bar{p}^s{}')$, in which $\hat{a}^s$ is the acceleration part of $\hat{x}^s$. The dynamic module of jammer trajectory is $p^s = \hat{p}^s + \frac{1}{2}u^sT^2$, $v^s = \hat{v}^s + u^sT$, $a^s = u^s$. The final output of jammer is x^s. When the UAV works in active state, it often uses measured value for correction. Therefore, x^s can be used as the measured value passed to the UAV state estimator, then the jammer can make $\hat{x}$ matched with x^s, which let the UAV fly along the wrong trajectory at last.

In Fig. 2, the estimator of UAV uses VD-Kalman filtering algorithm. When UAV moves with a constant velocity, it is in non- maneuvering mode, system model is as follow:

$$X(k) = AX(k-1) + BU(k-1) \tag{10}$$

In formula (10), $X(k) = \left[x(k)\quad V_x(k)\quad y(k)\quad V_y(k)\right]^T$, *A* is the state transition matrix, *B* is the control matrix. $U(k)$ is the process noise, $U(k) = \left[U_x(k)\ U_y(k)\right]^T$, $E[U(k)] = 0$, $E[U(k)U^T(j)] = Q\delta_{kj}$.

The measured model is:

$$Z(k) = HX(k) + V(k) \tag{11}$$

Where $H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$, $V(k)$ is a zero mean white noise whose covariance is *R*. It is uncorrelated with $U(k)$.

When the motion state of UAV is variable, system model is as follow:

$$X^m(k) = A^m X^m(k-1) + B^m U^m(k-1) \tag{12}$$

$$X^m(k) = \begin{bmatrix} x^m(k) & V_x{}^m(k) & y^m(k) & V_y{}^m(k) & a_y{}^m(k) & a_y{}^m(k) \end{bmatrix}^T$$

and A^m is the incremental dimension format of state transition matrix, B^m is the incremental dimension format of control matrix, $E[U^m(k)] = 0$, $E[U^m(k)U^{m^T}(j)] = Q^m \delta_{kj}$.

The measured model is the same as the model of non-maneuvering mode, the incremental dimension format of measured matrix is: $H^m = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$.

The general Kalman filtering algorithm is as follows:

$$\hat{X}(k/k-1) = A\hat{X}(k-1/k-1) + BU(k-1) \tag{13a}$$

$$P(k/k-1) = AP(k-1/k-1)A^T + GQ(k-1)G^T \tag{13b}$$

$$K(k) = P(k/k-1)H^T[HP(k/k-1)H^T + R]^{-1} \tag{13c}$$

$$\hat{X}(k/k) = \hat{X}(k/k-1) + K(k)[Z(k) - HX(k/k-1)] \tag{13d}$$

$$P(k/k) = P(k/k-1) - K(k)HP(k/k-1) \tag{13e}$$

Formulas (13a-b) explain the prediction process of the algorithm, formula (13a) describes the process of state transition, and formula (13b) represents the update of covariance. Formulas (13c-e) are the modification of the algorithm, *K* in formula (13c) is the Kalman coefficient that is used to calculate the proportion of prediction covariance in the sum of prediction covariance and measured covariance. Higher value of *K* means the greater probability of the true value close to the measured value and vice versa. Formulas (13d-e) are used to modify the state variables and covariance.

VD-Kalman filtering algorithm adopts non-maneuvering mode and maneuvering mode. A motion detector is used to judge the motion mode. If the former, filter will work in normal mode that has lower order, else filter will work in higher order mode until the motion returns to non-maneuvering mode.

The key issue of the algorithm is the maneuver detection. The filter works in normal mode at first, innovation sequence of the output is $v(k)$, $S(k)$ is the covariance matrix of $v(k)$. $\mu(k)$ and $\delta(k)$ are defined as follows:

$$\begin{aligned} \mu(k) &= \alpha\mu(k-1) + \delta(k) \\ \delta(k) &= v^T(k)S^{-1}(k)v(k) \end{aligned} \tag{14}$$

Let $\Delta = (1-\alpha)^{-1}$ be the window length of maneuver detection, maneuver detection is carried out as follows: if $\mu(k) \geq Th$, it is assumed that the target has got an acceleration at the time of $k-\Delta-1$, then non-maneuvering mode will change to maneuvering mode. The count value *m* counts from 0 to Δ, *m*=*m*+1 with each run of the maneuvering mode. So the maneuvering mode will be ran for at least Δ times.

The criterion used to make the filter mode return to non-maneuvering mode is the statistical significance of acceleration estimate. $\mu_a(k)$ and $\delta_a(k)$ are defined as follows:

$$\begin{aligned} \mu_a(k) &= \sum_{j-\Delta-1}^{k} \delta_a(j) \\ \delta_a(k) &= \hat{a}^T(k/k)[P_a^m(k/k)]^{-1}\hat{a}(k/k) \end{aligned} \tag{15}$$

In formula (15), $\hat{a}(k/k)$ is the acceleration estimate, $P_a^m(k/k)$ is the covariance of the acceleration. If $\mu_a(k) < Ta$, the acceleration estimate doesn't have the statistical significance and the filter will exit maneuvering mode.

The state estimator of jammer uses Kalman filtering algorithm under the second order Bayes estimators (GPB2). Based on the two working modes of UAV, which are non-maneuvering mode and maneuvering mode, GPB2 uses probability fusion of these two kinds of mode to comprehensively reflect the movement of the UAV, and to complete the correct trajectory tracking.

The likelihood function of the linear discrete system described in formulas (10)-(12) is:

$$\begin{aligned} p(z(k) \mid x(k)) = \exp[-\frac{1}{2}(z(k) - Hx(k))^T P^{-1}(z(k) \\ - Hx(k))] / \sqrt{2\pi \det(P)} \end{aligned} \tag{16}$$

P is the covariance of the Likelihood function that can be defined as follow:

$$\begin{aligned} P &= Cov(z(k) \mid x(k)) = Cov(Hx(k) + v(k)) \\ &= HP(k \mid k-1)H^T + R \end{aligned} \tag{17}$$

It is assumed that the likelihood functions of non-maneuvering mode and maneuvering mode using normal Kalman filtering algorithm are λ_{11} and λ_{21} respectively, using incremental dimension Kalman filtering algorithm are λ_{12} and λ_{22} respectively. The probabilities of adopting normal Kalman filtering algorithm and incremental dimension Kalman filtering algorithm are m_1 and m_2 respectively and their initial values are both 0.5. Considering the errors of the Kalman filter in altering modes, the probabilities of using normal Kalman filtering algorithm in non-maneuvering mode and maneuvering mode are set as 0.95 and 0.05 respectively, which are set as 0.05 and 0.95 respectively with incremental dimension Kalman filtering algorithm. The above choices of probabilities are based on the practice. Thus, the posterior probabilities in different conditions are:

$$p(x_{11}(k)\,|\,z(k)) = 0.95\lambda_{11}m_1$$
$$p(x_{21}(k)\,|\,z(k)) = 0.05\lambda_{21}m_1$$
$$p(x_{12}(k)\,|\,z(k)) = 0.05\lambda_{12}m_2 \quad (18)$$
$$p(x_{22}(k)\,|\,z(k)) = 0.95\lambda_{22}m_2$$

After the probability fusion, state values of non-maneuvering mode and maneuvering mode are $x(k)$ and $x_{VD}(k)$ respectively:

$$x(k) = p(x_{11}(k)\,|\,z(k))x_{11}(k) + p(x_{21}(k)\,|\,z(k))x_{21}(k) \quad (19)$$

$$x_{VD}(k) = p(x_{12}(k)\,|\,z(k))x_{12}(k) + p(x_{22}(k)\,|\,z(k))x_{22}(k) \quad (20)$$

To refresh the m_1 and m_2, introduce c_1 and c_2:

$$c_1 = 0.95\lambda_{11}m_1 + 0.05\lambda_{21}m_1$$
$$c_2 = 0.05\lambda_{12}m_2 + 0.95\lambda_{22}m_2 \quad (21)$$

Thus, $m_1 = c_1/(c_1+c_2)$, $m_2 = c_2/(c_1+c_2)$. The final output of state estimator is:

$$xout(k) = m_1x(k) + m_2x_{VD}(k) \quad (22)$$

From the above, jammer based on Bayesian estimation can complete the trajectory tracking of UAV in different modes.

IV. Simulation Verification

The total time of simulation is 800s. Let the target UAV start from (0, 0). When t= 0-400s, UAV flies along y axis with a constant velocity $v_y = -15m/s$. When t= 400-600s, there is a flat turn in the direction of x axis in trajectory with $a_x = a_y = 0.075m/s^2$. When the turn finishes, $v_x = 15m/s$, $v_y = 0m/s$, a_x and a_y drop to zero, then UAV will fly along the x axis until t=610s. When t=610-660s, there is a shape turn in the direction of y axis in trajectory with $a_x = a_y = -0.3m/s^2$. When the turn finishes, $v_x = 0m/s$, $v_y = -15m/s$, a_x and a_y drop to zero, then UAV will fly along the y axis until t=800s. The reference trajectory of jammer is a uniform straight line motion whose start point is (0, 0) and $v_x = 2.5m/s$, $v_y = -15m/s$. Let the observation errors of UAV and jammer in x and y direction be both 100 meters. The radar scan cycle is 2s, the parameter of UAV controller K^u=1, the parameter of UAV trajectory adjustment module G=0.6, the parameter of jammer controller K^s=1, the parameter of jammer trajectory adjustment module G^s=0.01.

UAV trajectories before and after jamming are shown as Fig. 3. It shows that UAV trajectory can be induced to the reference trajectory, but the deviation is obvious. To analyze it, NIS(normalized innovation squared) is defined as follow[15]:

$$NIS(k) = (z(k) - Hx(k))^T S(k)^{-1}(z(k) - Hx(k)) \quad (23)$$

$z(k)$ is the observation value at time of k, $Hx(k)$ is the prediction of observation value, $z(k)-Hx(k)$ is the innovation provided by $z(k)$. $S(k)$ is the prediction of error covariance matrix, it is defined as follow:

$$S(k) = HP(k\,|\,k-1)H^T + R \quad (24)$$

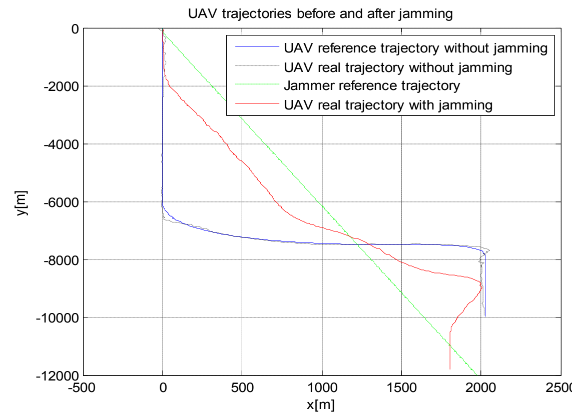

Fig. 3 UAV trajectories before and after jamming

NIS is used in the innovation detection of UAV navigation system. If NIS is greater than the threshold value, it means that the UAV is interfered by jammer. According to the simulation setting, NIS is a χ^2 distribution that has two degrees of freedom, by using the method of table lookup, 99% confidence interval is [0,9.21]. Fig. 4 is the output of NIS with direct track deception, which shows that the maximum of NIS is greater than 9.21, thus UAV with innovation detection will detect the jamming and trigger the alarm.

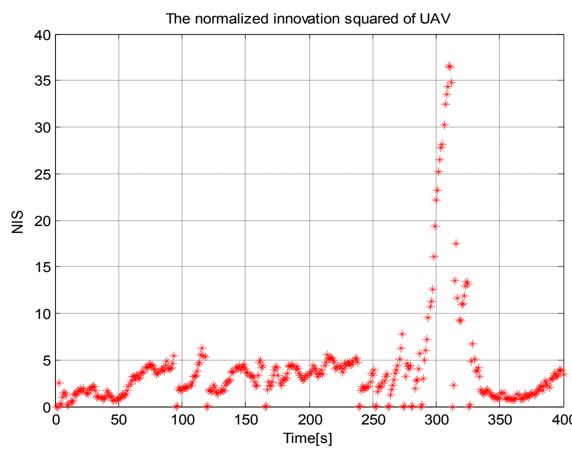

Fig. 4 NIS with direct track deception

To solve the problem of direct track deception, track fusion is presented to improve the secrecy of jamming. The purpose of track fusion is to make the UAV acceleration a match with jammer acceleration a^s. In the case of acceleration is zero, jammer will track and change the constant velocity part of UAV trajectory, jammer trajectory is $x^s = k_x\left(\bar{x} + \bar{x}^s\right)$; Otherwise, acceleration of jammer trajectory needs to match with that of UAV trajectory to adjust the output of jammer trajectory adjustment module. This is done to stabilize the result of UAV trajectory adjustment module and control the dynamic range of NIS. To achieve above effect, a judger is added in jammer, which is shown as Fig. 5.

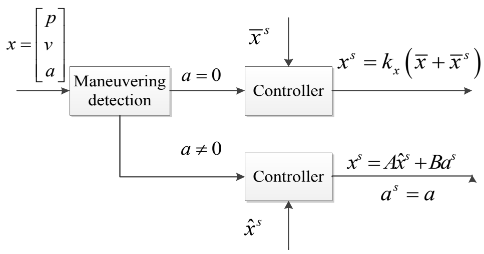

Fig. 5Improved controller of jammer

With the method of track fusion, let k_x be 0.5, jammer trajectory is a uniform motion along y axis with the velocity of -35m/s. The results of UAV trajectory and NIS are as shown in Fig. 6 and Fig. 7.

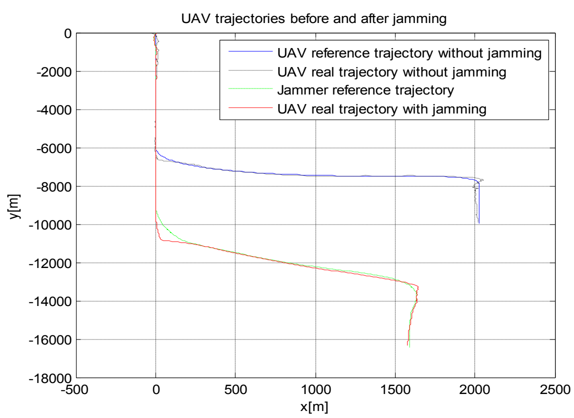

Fig. 6 UAV trajectory output with improved interference strategy

As Fig. 7 shows, the maximum of NIS is less than 9.21, which means jammer can avoid the innovation detection of UAV and accomplish the trajectory cheating.

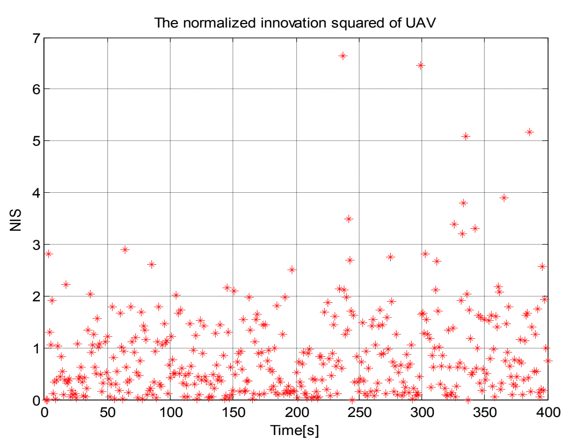

Fig. 7 NIS with improved interference strategy

V. CONCLUSION

In this paper, a strategy of trajectory cheating on the UAV is put forward. The carrier phase and code offset are adjusted to make the deceptive-jamming signal aligned with the true signal, which can control the track loop of the target UAV. So that the jammer can invade the UAV's navigation system in the tracking loop update interval. At the same time, the output of the UAV state estimator is changed by the deceptive-jamming signal that is regard as GPS measured value by the UAV. The simulation results show that the direct track deception and the track fusion both can make the UAV drift off the reference trajectory, specially, track fusion can avoid the interference detection and realize the trajectory cheating.

References

[1] Kim J H and Sukkarieh S, "A baro-altimeter augmented INS/GPS navigation system for an uninhabited aerial vehicle," International, 2003.

[2] H. L. QIN, L. L. CHAI and L. CONG, "Analysis on anti-jamming of GPS/INS ultra-tight coupled system," Computer Engineering and Design, vol. 34, issue 1, pp. 333-337, 2013.

[3] G. XIE, Principles of GPS and Receiver Design. Beijing, Publishing House of Electronics Industry, 2009.

[4] Humphreys T E, Ledvina B M and Psiaki M L, et al, "Assessing the Spoofing Threat: Development of a Portable GPS Civilian Spoofer," ION GNSS Conference, Sananah, 2008, pp. 2314-2325.

[5] Akos D M. "Who's Afraid of the Spoofer? GPS/GNSS Spoofing Detection via Automatic Gain Control (AGC)," Navigation - Journal of The Institute of Navigation, vol. 59, issue 4, pp. 281-290, 2012.

[6] K. CHEN, C. X. JI and Z. X. YAN, "The research of multiple model algorithm on radar tracking maneuvering target," Ship Science and Technology, vol. 26, issue 1, pp. 53-57, 2004.

[7] Ferrante J, "A Kalman filter-based radar track data fusion algorithm applied to a select ICBM case," IEEE Radar Conference, Philadelphia, 2004, pp. 457-462.

[8] Wendel J, Meister O, Schlaile C, et al, "An integrated GPS/MEMS-IMU navigation system for an autonomous helicopter," Aerospace Science & Technology, vol. 10, issue 6, pp. 527-533, 2006.

[9] Shepard D P, Bhatti J A and Humphreys T E, et al, "Evaluation of Smart Grid and Civilian UAV Vulnerability to GPS Spoofing Attacks," ION GNSS Conference, Nashville, 2012, pp. 3591-3605.

[10] JAMES BAO-YEN TSUI. Fundamentals Global Positioning system Receivers A Software Approach, Beijing: Publishing House of Electronics Industry, 2007.

[11] KAI BORRE. A Soft Ware-Defined GPS and Galileo Receiver. Beijing: National Defense Industry Press, 2009.

[12] H. S. ZHANG, G. G. GAO and L. KOU et al, "Deceptive Jamming Technology of GPS Based on Track Induction Method," Journal of Projectiles Rockets Missiles and Guidance, vol. 33, issue 3, pp. 149-152, 2013

[13] Kendoul F. "Survey of advances in guidance, navigation, and control of unmanned rotorcraft systems," Journal of Field Robotics, vol. 29, issue 2, pp. 315-378, 2012.

[14] X. R. CHEN and S. F. CHEN, "Variable dimension of Kalman filter for target tracking," Chinese Journal of Scientific Instrument, vol. 27, issue 9, pp. 1163-1166, 2006.

[15] Bar-Shalom, Yaakov, Kirubarajan, Thiagalingam, Li, X.-Rong, "Estimation with Applications to Tracking and Navigation," Applied Neuropsychology Child, vol. 34, issue 2, pp. 727-736, 2001.