RESEARCH ON AGRICULTURE SURVEY AND EVALUATION UAV NAVIGATION SYSTEM
/
农业勘查评估无人机导航系统研究

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Abstract: *Agriculture survey and evaluation UAV is kind of advanced high-efficiency agriculture information equipment that can be used to farmland measurement, agricultural insurance assessments and other fields. BeiDou Navigation Satellite System is China's global navigation satellite system which has been developed independently , and currently it is rarely applied in agriculture survey and evaluation UAV. Since BeiDou navigation system can only provide location information, an integrated navigation system that composed by BeiDou Navigation Satellite System, Strapdown Inertial Navigation System and Air Data System is proposed to improve the navigation accuracy of UAV navigation system. Integrated navigation system model is established, and to improve the navigation system parameters solving speed, and also to overcome the filtering divergence phenomenon caused by the system model uncertainty, a modified two-step adaptive Kalman filter algorithm for navigation parameters solving is proposed. Simulation results show that the proposed integrated navigation system and parameters solving algorithm can effectively improve the UAV navigation accuracy and prevent divergence of the filter.*

Keywords: *agriculture survey and evaluation; BeiDou navigation satellite system; integrated navigation system; Kalman filter*

INTRODUCTION

To begin with we will provide a brief background on the civilian Unmanned Aerial Vehicle (UAV). In recent years, the research of civilian UAV has made great progress, and it is applied in more and more fields, such as communications relay, weather detection, disaster monitoring, pesticide spraying, geological surveying, mapping, traffic control, and many other fields [5,9]. Agriculture survey and evaluation UAV is kind of advanced high-efficiency agriculture information equipment, which can be used to measure farmland, agricultural insurance assessments and other fields.

Currently the main navigation technologies used in UAV are Global Positioning System (GPS) and Strapdown Inertial Navigation System (SINS). Single navigation technology has its own shortcomings. In the filed of UAV navigation, the usually employed navigation method is the integrated navigation method that used the above two method. SINS can not only provide real-time position, velocity and attitude and other navigation information, but also have the characteristics such as fast, better dynamic performance and high accuracy in short term [6]. GPS have several advantages such as higher positioning and velocity precision, and not accumulated with time growth. However, it can not be absolute dependent because it is controlled by the America Government [2]. BeiDou Navigation Satellite System (BD) is China's self-developed global satellite navigation system. From December 27, 2012 the BD has provide navigation services officially, the service covers most of the Asia-Pacific region, and can provide services such as positioning, velocity

***摘要**：农业勘查评估无人机是一种先进的高效农业信息化设备，可用于农田测量、农业保险评估等领域。北斗卫星导航系统是我国自主设计和研发的卫星导航系统，目前在民用无人机上的应用较少。由于北斗导航系统只能提供位置信息，为提高无人机导航系统的导航精度，提出将其与捷联惯导系统、大气数据系统组合构成组合导航系统。推导建立了组合导航系统模型，为提高导航参数解算速度克服系统模型的不确定性带来的滤波发散现象，提出采用一种改进的两步自适应卡尔曼滤波算法进行导航参数解算。仿真结果表明，本文提出的组合导航系统及参数解算算法，可有效提高民用无人机的导航精度，防止滤波发散。*

关键词: *农业勘查评估, 北斗卫星导航系统, 组合导航系统, 卡尔曼滤波*

引言

在文章的开始我们将给出民用无人机的研究背景。民用无人机的研究在最近几年有了很大的进展，应用领域也越来越广，可用于通信中继、气象探测、灾害监测、农药喷洒、地质勘测、地图测绘、交通管制等诸多领域 [5, 9]。农业勘查评估无人机是一种先进的高效农业信息化设备，可用于农田测量、农业保险评估等领域。

目前在无人机上采用的导航技术主要为 GPS 导航和捷联惯性导航。单一的导航技术都有各自的缺点，因此在无人机导航中，一般采用上述两种导航方式进行组合导航。惯性导航系统不仅可以连续、实时地提供位置、速度和姿态等多种导航信息，而且具有快速、动态性能好、短期精度高等特性 [6]。GPS 具有定位和测速精度高、不随着时间增长而积累等优点。但是，其使用权受制于人，不能绝对依赖[2]。北斗卫星导航系统是我国在实施的自主发展、独立运行的全球卫星导航系统。北斗卫星导航系统于 2012 年 12 月 27 日起正式提供导航服务，服务范围涵盖亚太大部分地区，提供定位、测速、授时服务[1]。北斗卫星导航系统必将在民用上和军事上发挥重大作用。

measurement, timing and so on [1]. BD will play an important role in the civilian and military filed.

Since BD has just been put into service, then there are fewer applications in UAV, let alone in agriculture survey and evaluation UAV. In this article the BD is applied to agriculture survey and evaluation UAV navigation. However, the BD have some shortcomings such as positioning accuracy is not high, the signal is easily lost, and so on. Air Data System (ADS) can obtain the airspeed and pressure altitude information of the UAV through pressure, temperature and other information got from the atmospheric sensors installed in the UAV. The ADS does not depend on external conditions., being very independent. The BD, ISINS and ADS are combined, then an autonomous BD/SINS/ADS integrated agriculture survey and evaluation UAV navigation system is constructed.

In this paper, the BD/SINS/ADS intergraded navigation system is researched; we shall first briefly establish the system model. An improved two step adaptive Kalman filter algorithm is applied in this system, and this algorithm can solve such questions as filtering divergence phenomenon, and also this algorithm can improve the settlement rate which can be provided [3]. The integrated navigation system and the filtering algorithm have great practical value.

MATERIAL AND METHOD

Error Model

We will provide in this section a basic error model needed in the following Section. In this section, the error model includes barometric altimeter error model, inertial device error model and the air data computation model is given, the error model as follows.

(1) Barometric altimeter error model

The barometric altimeter error has relevant with non-linear relationship between hydrostatic and altitude, errors caused by temperature compensation inaccurate and pressure method errors. In the integrated navigation system, the general barometric altimeter error is approximately described by a first order Markov process [7],

由于北斗导航系统刚投入使用，目前将其应用到民用无人机导航的较少，在农业勘查与评估无人机中的应用更少。本文将北斗导航应用到民用无人机的导航中，但北斗单独导航存在定位精度不高、信号容易丢失等现象，

大气数据系统可以通过安装在无人机上的大气传感器得到的压力、温度等信息获得无人机的速度和气压高度信息。 大气数据系统不依赖于外部条件，具有很强的独立性。将北斗导航系统、捷联惯导系统、由安装在机体上的大气传感器构成的大气数据数据系统等组合起来，构建了自主的 BD/SINS/ADS 组合的民用无人机导航系统。

本文以民用无人机的 BD/SINS/ADS 组合系统为研究背景，首先建立了系统的模型，并针对导航参数解算中可能出现的滤波发散现象，以及提高结算速度，提出应用一种改进的两步自适应卡尔曼滤波算法 [3]。该组合导航系统及滤波算法有较大的实际应用价值。

材料与方法

误差模型

在本章将给出后文需要的误差模型，误差模型包括：气压高度表误差模型、惯性器件误差模型和大气数据计算模型，误差模型如下：

（1）气压高度表误差模型

影响气压高度表误差有静压与高度间的非线性关系、温度补偿不准确引起的误差、气压方法误差等。在组合导航系统中，一般把气压高度表误差用一阶 Markov 过程近似描述[7]：

$$\delta\dot{h}_b = -\frac{1}{\tau_b}\delta h_b + \omega_b, \qquad (1)$$

Where δh_b is the barometric altimeter error, τ_b is relevant time, and ω_b is measurement noise.

(2) Inertial device error model

Inertial device includes three gyros and three accelerometers. Gyro drift consists of three components, that is random constant drift, relevant drift and unrelevant drift. The relevant time of relevant drift is generally greater than 1 hour. In terms of short range UAV studied in this paper, this relevant drift can be approximated by random constant, and compared with the random constant drift, this relevant drift 1-2 orders of magnitude is smaller, so the gyro drift model can be simplified as constant drift ε_x , ε_y and ε_z and white noise components ω_x , ω_y and ω_z , and,

式中，δh_b 为气压高度表误差，τ_b 为相关时间，ω_b 为测量噪声。

（2）惯性器件误差模型

惯性器件包括陀螺仪和加速度计。陀螺漂移包含三种分量：随机常值漂移、相关漂移和不相关漂移。相关漂移的相关时间一般大于 1 小时，对本文研究的短航程无人机来讲，这种相关漂移可近似为随机常数，且与随机常值漂移相比，这种漂移小 1-2 个数量级，所以初始对准中陀螺漂移模型可简化为常值漂移 ε_E 、ε_N 、ε_U 和白噪声分量 ω_E 、ω_N 、ω_U ，且有：

$$\begin{cases} \dot{\varepsilon}_x = 0 \\ \dot{\varepsilon}_y = 0, \\ \dot{\varepsilon}_z = 0 \end{cases} \qquad (2)$$

Similar to the gyro drift model, the accelerometer drift also contains the above three kinds of components. The relevant drift is relatively small, and at the same time in order to reduce the dimensions of the filter, the error model of the accelerometer is also simplified by random constant drift ∇_x, ∇_y and ∇_z and white noise components.

(3) The air data computation model

According to the parameters such as the pressure, temperature and so on that were provided by the atmospheric sensors installed in the body of UAV, based on the atmospheric parameter model, the airspeed, altitude and other information of the UAV are solved by the Air Data System directly. In this paper, the low-altitude UAV is studied, and its flight altitude is below 500 meters.

Assuming the atmosphere sensor pressure sensor is P_s, total pressure is P_t, temperature is T, then pressure altitude formula is calculated as follows[8]:

与陀螺仪漂移模型类似，加速度计的漂移也包含上述三种分量。相关漂移相对较小，同时也为了使滤波器的维数降低，所以加速度计的误差模型也简化为由随机常数漂移 ∇_E、∇_N、∇_U 和白噪声分量组成。

（3）大气数据计算模型

大气数据系统通过安装在机体上的大气传感器提供的压力、温度等参数，根据大气参数模型直接解算载体的空速、气压高度等信息。本文研究的是低空无人机，飞行高度在500米以下。

假设大气传感器静压为 P_s，总压为 P_t，温度为 T，则气压高度 H_p 公式计算如下[8]：

$$H_p = 145442\times\left[1-\left(\frac{P_s}{29.9213}\right)^{0.19026}\right], \tag{3}$$

According to the total atmospheric pressure P_t measured by the atmospheric sensor, and the atmospheric density ρ about the altitude of the UAV situated, the indicated airspeed can be calculated as follows.

根据大气传感器测得的总压 p_t，载体所处高度的大气密度 ρ，可计算指示空速：

$$V_s = \sqrt{2\times P_t/\rho}, \tag{4}$$

Next, the following formula is used to convert the indicated airspeed to true airspeed,

接下来利用下式将指示空速转化真空速：

$$V_t = V_s\times\left[1+\left(1-Hp\right)\times 0.05/1000\right], \tag{5}$$

If the wind velocity is small during UAV operation, due to system accuracy limitations, wind velocity can be approximately zero; if the wind velocity is large, the algorithm proposed by the reference [4] can be used to estimate wind velocity. If the wind velocity information of UAV location is obtained, then the following formula can be used to calculate the UAV’s ground velocity,

如果无人机运行时风速较小，由于系统精度限制，可将风速近似为零；若风速较大，可根据文献[4]提出的算法利用相关信息进行风速的估算。得到无人机所处位置的风速信息，即可利用下式计算出载体的对地速度：

$$V_g = V_t + V_w, \tag{6}$$

V_w is the wind velocity vector, V_g is the ground velocity vector, and V_t is true airspeed vector.

Integrated navigation model

(1) State equation

State equation of the UAV navigation system composed by three errors equation include velocity error, position error and platform misalignment angle error equation. According to the mechanics choreography equation and attitude error equation of SINS system, the state equations of the integrated navigation system can be obtained as follows,

V_w 为风速矢量，V_g 为地速矢量，V_t 真空速矢量。

组合导航模型

（1）状态方程

无人机导航系统状态方程由速度误差、位置误差和平台失准角误差方程构成。根据 SINS 系统的力学编排方程和姿态误差方程，可以获得组合导航系统的状态方程：

$$\dot{X}(t) = F(t)X(t) + G(t)W(t), \tag{7}$$

Wherein W is irrelevant white noise with zero mean, and it satisfied $E[W(t)W^T(\tau)] = Q(t)\delta(t-\tau)$.

State variables are

其中，W 为不相关的零均值白噪声，满足 $E[W(t)W^T(\tau)] = Q(t)\delta(t-\tau)$。

状态变量为

$$X(t) = \left[\phi_x,\phi_y,\phi_z,\delta v_x,\delta v_y,\delta v_z,\delta L,\delta\lambda,\delta h,\delta h_b,\varepsilon_x,\varepsilon_y,\varepsilon_z,\nabla_x,\nabla_y,\nabla_z\right]^T, \tag{8}$$

Where, ϕ_x, ϕ_y and ϕ_z is platform error angle; δv_x, δv_y and δv_z is the velocity error along the east, north and up direction; δL, $\delta\lambda$ and δh is latitude, longitude and altitude error. The rest are gyroscopes and accelerometers

其中，ϕ_x、ϕ_y、ϕ_z 为平台误差角，δv_x、δv_y、δv_z 为沿东、北、天方向的速度误差，δL、$\delta\lambda$、δh 为纬度、经度误差和高度误差，其余为陀螺仪和加速度计的常值误

constant error, and noise modeling of gyroscopes and accelerometers re zero mean white noise. $F(t)$ is the state transition matrix of dimensions of 16 multiplied by 16.

(2) Measurement equation

Chose velocity difference between the UAV ground velocity vector obtained from the Air Data System converted to the navigation frame velocity and the SINS velocity, position difference between the UAV position obtained from the BD receiver and the latitude and longitude information of the SINS, and altitude error between height value measured by Air Data System and SINS altitude as measurements, the following measure equation can be constructed,

差，陀螺仪和加速度计的噪声建模为零均值白噪声。$F(t)$ 为 16*16 维的状态转移矩阵。

（2）量测方程

将由大气数据系统得到的载体的地速转换为导航坐标系速度后与 SINS 速度之差、将北斗接收机给出的无人机位置信息与 SINS 的经纬度信息之差及大气数据系统测量到的高度值与惯导高度之差作为观测量，构建如下的量测方程：

$$Z(t)=\begin{bmatrix} v_{SINSx}-v_{ADSx} \\ v_{SINSy}-v_{ADSy} \\ v_{SINSz}-v_{ADSz} \\ L_{SINS}-L_{BD-2} \\ \lambda_{SINS}-\lambda_{BD-2} \\ h_{SINS}-h_{ADS} \end{bmatrix}=\begin{bmatrix} \delta v_x+V_1 \\ \delta v_y+V_2 \\ \delta v_z+V_3 \\ \delta L+V_4 \\ \delta\lambda+V_5 \\ \delta h+V_6 \end{bmatrix}=H(t)X(t)+V(t), \tag{9}$$

Where $H(1,4)=H(2,5)=H(3,6)=1$, $H(4,7)=H(5,8)=H(6,9)=1$, and $V(t)$ is the measurement noise.

The two-step adaptive Kalman filter

Because the on load ability of the UAV is limited, thus the calculation speed is affected, and the fast filtering algorithm is needed. In the two-step Kalman filtering algorithm, the Kalman filter is decomposed into two parallel reductions that filtering respectively, and the reduced order filter greatly reduces the amount of calculation.

In order to improve the filtering speed, the two-step Kalman filtering algorithm is used as navigation solver. Because of the mathematical model and noise statistical model of the SINS, ADS and BD system is not accurate, so that the model and the obtained measurement values do not match, which will lead to filtering divergence. Therefore the traditional two-step Kalman filtering algorithms is improved as adaptive filtering, which can restrain the divergence of Kalman filter, and can improve the navigation accuracy of the integrated navigation system.

Consider the following linear discrete stochastic systems,

式中：$H(1,4)=H(2,5)=H(3,6)=1$，$H(4,7)=H(5,8)=H(6,9)=1$，$V(t)$ 为量测噪声。

两步自适应卡尔曼滤波器

由于无人机带负载能力有限，因此其计算速度受到影响，需要有快速的滤波算法。两步卡尔曼滤波算法卡尔曼滤波器分解成两个平行的降阶滤波器分别进行滤波计算，大大降低了计算量。

为提高滤波速度，本文将采用两步卡尔曼滤波算法进行导航解算。由于惯性器件、大气数据系统、北斗系统的数学模型和噪声的统计模型不准确，使模型与获得的量测值不匹配，会导致滤波器发散。因此本文将传统的两步卡尔曼滤波算法改进为自适应滤波器，可抑制滤波发散，提高导航精度。

考虑以下线性离散随机系统：

$$x_k=A_{k-1}x_{k-1}+B_{k-1}b_{k-1}+\xi_{k+1}, \tag{10}$$

$$b_{k+1}=b_k, \tag{11}$$

$$y_k=H_kx_k+\eta_k, \tag{12}$$

Where x_k is the state of the system; b_k is the deviation vector; ξ_k is the process noise vector, $E\left[\xi_k\xi_l^T\right]=Q_k\delta_{kl}$; η_k is the measurement noise vector.

The first step is to ignore the deviation term (that is let $b=0$), and add the adaptive filter, then the unbiased filter can be constituted as follows,

式中：x_k 为系统状态；b_k 为偏差向量；ξ_k 为过程噪声向量，$E\left[\xi_k\xi_l^T\right]=Q_k\delta_{kl}$；$\eta_k$ 为量测噪声向量，$E\left[\eta_k\eta_l^T\right]=R_k\delta_{kl}$。

第一步是忽略偏差项（即令 $b=0$），并加入自适应环节，构成无偏差滤波器：

$$\bar{x}_k=A_{k-1}\tilde{x}_{k-1}, \tag{13}$$

$$\tilde{x}_k=\bar{x}_k+\tilde{K}_x(k)\tilde{r}_k, \tag{14}$$

$$\bar{y}_k=H_k\bar{x}_k, \tag{15}$$

$$\tilde{r}_k=y_k-\bar{y}_k, \tag{16}$$

$$\tilde{K}_x(k)=\tilde{P}_x(k)H_k^T\left[H_k\tilde{P}_x(k)H_k^T+R_k\right]^{-1}, \tag{17}$$

$$\tilde{P}_x(k)=A_{k-1}\tilde{T}_x(k-1)A_{k-1}^T+Q_k, \tag{18}$$

$$\tilde{T}_x(k)=\left(I-\tilde{K}_xH_k\right)\tilde{P}_x(k), \tag{19}$$

$$\tilde{K}_x(k)=\left[\tilde{\Gamma}_x(k)H_k^T-\tilde{F}_x(k)H_k^T\right]\left[\tilde{C}_0(k)-H_k\tilde{F}_x(k)H_k^T\right]^{-1}, \tag{20}$$

$$M=\left[HA \quad HA^2 \quad \cdots \quad HA^n\right]^T, \tag{21}$$

$$\tilde{\Gamma}_x(k)H_k^T=\left(M^TM\right)^{-1}M^T\begin{bmatrix}\tilde{C}_1(k)\\ \tilde{C}_2(k)\\ \vdots\\ \tilde{C}_n(k)\end{bmatrix}, \tag{22}$$

$$\tilde{F}_x(k)=A_{k-1}\left[\tilde{F}_x(k)+\left(\tilde{\Gamma}_x(k)-\tilde{F}_x(k)\right)H_k^T\left(\tilde{C}_0(k)-H_k\tilde{F}_x(k)H_k^T\right)^{-1}H_k\left(\tilde{\Gamma}_x(k)-\tilde{F}_x(k)\right)^T\right]A_{k-1}^T, \tag{23}$$

$$\tilde{C}_i(k)=\tilde{C}_i(k-1)+\left(y_ky_{k-i}^T-\tilde{C}_i(k-1)\right)/k, \tag{24}$$

Where $\tilde{x}_{(\bullet)}$ means state estimation value obtained by ignoring the deviation; $\tilde{P}_x$ is the error covariance about $\tilde{x}_{(\bullet)}$.

The second step is estimated deviation vector from residuals of the unbiased filter, and then deviation filter can be obtained.

式中：$\tilde{x}_{(\bullet)}$ 表示忽略偏差后得到的状态估计值；$\tilde{P}_x$ 为 $\tilde{x}_{(\bullet)}$ 的误差协方差。

第二步是从无偏差滤波器的残差序列中估计偏差向量，得到偏差滤波器。

$$U_x(k+1)=A_kV_x(k)+B_k, \tag{25}$$

$$S(k)=H_kU_x(k)+C_k, \tag{26}$$

$$V_x(k)=U_x(k)-\tilde{K}_x(k)S(k), \tag{27}$$

$$M(k+1)=M(k)-M(k)S^T(k)\left[H_k\tilde{P}_x(k)H_k^T+R_k+S(k)M(k)S^T(k)\right]^{-1}S(k)M(k), \tag{28}$$

$$K_b(k)=M(k+1)\left[V_x^T(k)H_k^T+C_k^T\right]R_k^{-1}, \tag{29}$$

$$\hat{b}_k=\left[I-K_b(k)S(k)\right]\hat{b}_{k-1}+K_b(k)\tilde{r}_k, \tag{30}$$

$$\delta_k=V_x(k)\hat{b}_k, \tag{31}$$

The estimate of the linear discrete systems containing deviation can be obtained by adding results of the two sub-filters,

最后将两个子滤波器得到的结果相加，即得到对含有偏差的线性离散系统的估计：

$$\hat{x}_k=\tilde{x}_k+\delta_k, \tag{32}$$

RESULTS

Simulation results

In order to verify the effectiveness of the proposed integrated navigation method and filtering method, the computer simulation experiment was carried out. UAV motion model was generated by aircraft modules in aerosim toolbox in Matlab, and a track including linear motion, acceleration, turning, circling, climbing, descend and other state of the UAV were designed.

A simulation experiment was done and 500 seconds simulation data were used. SINS sampling frequency is 100hz, BD data sampling period is 1 s, combined period is 1 s. In simulation experiments, the gyro constant drift is 0.2 °/ h, accelerometer zero bias is $10^{-4}g$. The initial position errors are 5 m, 5 m and 10 m respectively; the initial velocity error is 0.1 m/s; initial platform misalignment error of 20", 20" and 50" respectively. The measurement noise of the BD receiver is white noise, and the standard deviation of the white noise is 8 m.

In order to illustrate the problem better, in this paper simulation experiment of SINS and SINS/BD/ADS integrated navigation system were done, respectively. The traditional Kalman filter algorithm and the improved two-

结果

仿真结果

为了验证本文所提组合导航方法及滤波方法的有效性，进行了计算机仿真实验。利用 Matlab 中 Aerosim 工具箱中的飞行器模块生成无人机运动模型，并设计一条包括匀速直线运动、加速、转弯、盘旋、爬升、降落等状态的航迹。

取一组 500s 的模拟数据进行仿真实验验证。SINS 采样频率为 100Hz，北斗数据采样周期为 1s，组合周期为 1s。仿真中陀螺仪常值漂移 0. 2°/h，加速度计零偏 $10^{-4}g$。初始位置误差分别为 5m、5m 和 10m；初始速度误差为 0. 1 m/s；初始平台失准误差分别为 20"、20"和 50"。北斗接收机测量噪声为标准差为 8 m 的白噪声

为了更好的说明问题，本文分别对 SINS、BD/SINS/ADS 组合导航系统进行了仿真实验，对上述两系

step adaptive Kalman filter proposed in this paper were employed in above two systems respectively to calculate the navigation parameter. According to the estimation of the error of navigation parameters, navigation parameters of the integrated navigation system were corrected.

The simulation results shown in Figure 1 and Figure 2, where the dotted line was the result for the SINS system using conventional Kalman filter, and the solid line was the result for the SINS / BD / ADS integrated navigation system with improved two-stage adaptive Kalman filter algorithm.

统分别采用传统 Kalman 滤波算法、本文提出的改进的两步自适应卡尔曼滤波器进行导航参数的解算，并根据估计的导航参数误差，修正组合导航系统的导航参数。

仿真结果见图 1、图 2，其中虚线曲线为对 SINS 系统应用传统 Kalman 滤波算法的结果，实线为对 BD/SINS/ADS 组合导航系统应用改进的两步自适应卡尔曼滤波算法的结果。

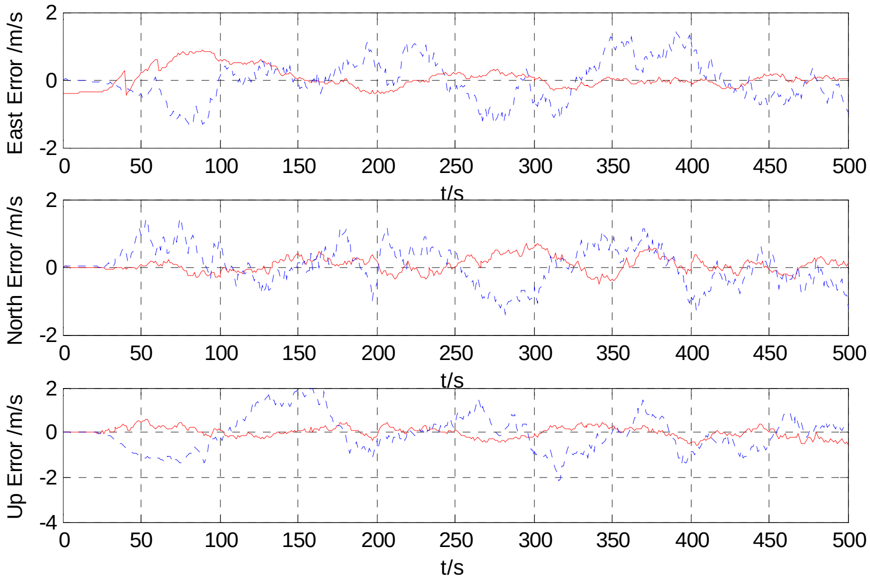

Fig. 1 - Velocity error curve / *速度误差曲线*

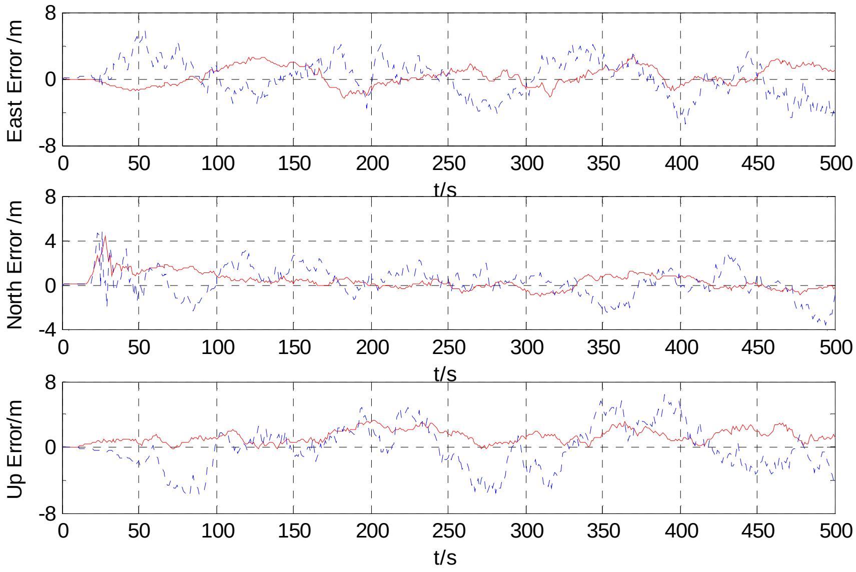

Fig. 2 - Position error curve / *位置误差曲线*

From figure 1 and figure 2, the simulation calculation results showed that due to the influence of various factors such as noise and error, navigation precision of single navigation mode is low. And for long time navigation the navigation parameters which are obtained by SINS calculating would be divergent. As the BeiDou Navigation Satellite System and the Air Data System were introduced in BD/SINS/ADS integrated pattern, their position and velocity information also were introduced, and then the velocity error and position error convergence rate is improved obviously. The system has good fault tolerance performance and can effectively restrain the error caused

从图 1、图 2 的仿真计算结果可以看出，由于各种噪声和误差等因素的影响 SINS 单一导航模式导航精度较低，而且长时间导航由 SINS 解算得到的导航参数会发散。而 BD/SINS/ADS 组合模式由于增加了北斗卫星导航系统和大气数据系统，引入了位置和速度信息，使得速度误差和位置误差的收敛速度有明显提高，具有较好的容错性能，可以有效地抑制由陀螺漂移引起的误差，提高整个导航系统的精

by the gyro drift and improve the precision of navigation system. At the same time the adaptive two step Kalman filter is adopted to avoid the divergence of navigation parameters.

Prototype UAV

In this paper, the prototype UAV of the agriculture survey and evaluation UAV we studied, is electronically moving fixed-wing UAV and technical indicators of the UAV as follows.

The takeoff gross weight is 10kg, flight altitude is 800m, cruising speed is 50km/h, the tasks load is 3-5kg, life time is 1 hour, engine power 2kw, and 3 maximum wind resistances. The prototype UAV that can be seen in figure 3, and figure 4 is flight test image.

度，同时采用了两步自适应卡尔曼滤波器，避免了导航参数的发散。

无人机样机

在本文中，农业勘查评估无人机是电动固定翼无人机，技术指标如下。

起飞总重量为 10 公斤，飞行高度为 800 米，巡航速度 50 公里每小时，任务负载 3-5KG，续航时间为 1 小时，发动机功率 2kw，最大可抗 3 级风。无人机样机见图 3，图 4 是飞行测试图像。

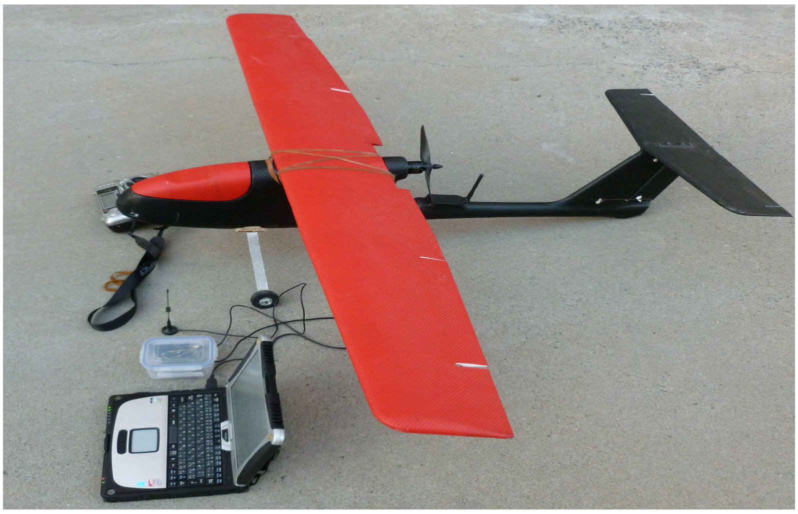

Fig. 3 - Prototype UAV / *无人机样机*

Fig. 4 - Flight test image / *飞行测试图像*

CONCLUSIONS

For the reason that the right of GPS controlled by others and lack of autonomy, the BD system is studied in the application of the agriculture survey and evaluation UAV navigation system. In order to improve the agriculture survey and evaluation UAV navigation system precision, BD/SINS/ADS integrated navigation system is proposed in this paper. The system has better fault tolerance performance, and external reference information is introduced to improve the navigation precision and reliability of the navigation system.

Because of the uncertainty of the model, filtering divergence phenomenon will appear in the process of filtering. To prevent the happening of the filtering divergence, an

结论

针对 GPS 使用权受制于人，缺乏自主性，研究了北斗系统在无人机导航系统中的应用。为提高无人机导航系统精度，提出采用 BD/SINS/ADS 组合导航系统，该系统具有较好的容错性能，引入了多种外部参考信息，可以提高导航系统的导航精度和可靠性。

由于模型的不确定性，滤波过程中会出现滤波发散现

improved two-step adaptive Kalman filter algorithm is proposed. This algorithm can not only improve the calculating speed but also avoid filtering divergence. In this paper, a numerical simulation results show that the proposed BD/SINS/ADS integrated navigation system and improved two-step adaptive Kalman filter navigation algorithm can effectively improve the agriculture survey and evaluation UAV navigation accuracy.

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象。为防止滤波发散现象的发生，本文提出了一种改进的两步自适应卡尔曼滤波算法，可以提高解算速度，避免滤波发散。本文进行了数值仿真，结果表明本文提出的组合导航系统及导航算法可有效提高导航精度。

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