

异类传感器融合跟踪系统配准偏差的在线补偿

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摘要: 针对多传感器融合跟踪系统的时变配准偏差补偿问题, 提出了一种配准偏差的在线估计和补偿算法. 该算法首先依据多传感器提供的测量和跟踪信息, 建立配准偏差的动态模型, 然后利用极小化似然函数结合卡尔曼滤波方法在线估计系统偏差, 利用估计的配准偏差, 补偿和修正跟踪器的测量信息, 实现多传感器的融合跟踪. 最后针对异类传感器(雷达、红外)组成的多传感器跟踪系统, 给出了应用该方法的仿真结果.

关键词: 多传感器; 配准; 补偿; 融合; 跟踪

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On-line bias compensation for dissimilar sensor fusion tracking

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Abstract: For the time-variant registration errors of multi-sensor fusion tracking system, an on-line bias estimation and compensation algorithm for multi-sensor fusion tracking is proposed. A dynamic model of the bias is formulated based on the target information of measurements and estimation. A minimization of the likelihood function and Kalman filter are used to estimate the bias on-line, and the measurements are compensated for estimated bias. Finally, an example for the estimation of the bias parameters of radar andIRST sensors is given to illustrate the effectiveness of the approach.

Key words: multi-sensor; registration; compensation; fusion; track

1 引言(Introduction)

在多传感器构成的传感器网络探测跟踪系统中, 为了获得目标的“统一”信息, 需把各传感器测得的数据转换到公共参考坐标系中, 但由于传感器的系统偏差和测量误差的存在, 对多目标跟踪系统中的跟踪门计算、轨迹状态和轨迹协方差矩阵的估计、以及测量和轨迹的关联准则等都产生不利影响^[1], 因此在多传感器融合跟踪系统中, 首先要对数据进行多传感器的时间和空间配准. 针对空间配准问题, Friedland B^[2]和 Inagni M 先后采用卡尔曼滤波两级卡尔曼滤波估计器方法研究了状态和偏差的联合估计问题, 但算法都基于偏差的先验信息; Leung H^[3]提出的最小二乘法, 采用了基于二维平面中立体投影方法, 对不同传感器的偏差进行估计, 但算法未考虑各传感器相对于公共坐标系的偏差的影响. Nabaa^[4]采用目标的非线性转换坐标机动模型, 对分布式传感器的位置误差和方向误差进行估计, 但要求传感器无测量噪声. 虽然 Helmick^[5]考虑测量噪声和相对于公共坐标系的偏差的影响, 并利用卡尔曼

滤波估计传感器的配准误差和姿势误差, 但该算法只适用于传感器的配准误差和姿态误差较小的情况. Karniely^[6]提出了运用神经网络方法来估计传感器的各类偏差, 但神经网络的训练需要离线进行, 不能满足实时性要求和配准偏差时变的情况. 现有的许多配准算法通常只针对定常配准偏差进行离线估计, 并对配准偏差模型做了不同程度的简化假设, 对时变配准偏差补偿问题未作深入研究. 本文针对多传感器系统配准偏差的动态补偿问题, 提出了一种配准偏差的在线估计和补偿算法, 其原理如图1所示:

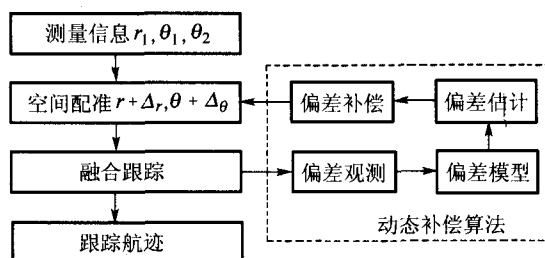


图1 在线配准偏差补偿算法原理图

Fig. 1 Principle scheme of on-line bias compensation

算法的工作过程是:依据多传感器提供的测量和跟踪信息,形成测量数据对,当采样周期到时,利用测量数据对建立配准偏差的初始值和初始协方差,然后根据卡尔曼滤波方法估计出的系统偏差,补偿和修正跟踪器的测量更新方程,实现多传感器的融合跟踪。

2 配准偏差模型(Model of registration)

假设 $K(K \geq 2)$ 个传感器,对同一目标进行测量,令 $\{\Delta_t\}$ 表示系统偏差, $\{S_t\}$ 表示目标的状态观测测量,测量值 $y_{i,t}$ 表示第 i 个传感器在 t 时刻的测量值,则

$$y_{i,t} = f_i(\Delta_t, S_t) + g_i(\Delta_t, S_t)n_{i,t}. \quad (1)$$

其中 $\{n_{i,t}\}$ 为标准高斯白噪声序列, $\{n_{i,t}\}, \{\Delta_t\}, \{S_t\}$ 相互独立。

将式(1)在 $(\bar{\Delta}_t, \bar{S}_t)$ 处进行泰勒级数展开,并略去二阶以上高阶项,整理得

$$y_{i,t} - \bar{y}_{i,t} \approx F_{S,i,t}(S_t - \bar{S}_t) + F_{\Delta,i,t}(\Delta_t - \bar{\Delta}_t) + G_{i,t}n_{i,t}. \quad (2)$$

其中:

$$\begin{aligned} \bar{y}_{i,t} &\equiv f_i(\bar{\Delta}_t, \bar{S}_t), \quad G_{i,t} \equiv g_i(\bar{\Delta}_t, \bar{S}_t), \\ (F_{S,i,t})_{jk} &\equiv \frac{\partial f_{ij}}{\partial S_{i,k}}(\bar{Z}_t), \\ F_{\Delta,i,t} &= [0 \quad \cdots \quad 0 \quad \cdots \quad F_{\Delta,i,t} \quad 0 \quad \cdots \quad 0], \\ (F_{\Delta,i,t}) &= \frac{\partial f_{ij}}{\partial \Delta_{i,k}}(\bar{Z}_t), \end{aligned}$$

$$Z_t^T = [\Delta_t^T, S_t^T], \quad \Delta_t^T \equiv [\Delta_{1,t}^T \quad \cdots \quad \Delta_{K,t}^T],$$

T 表示矩阵的转置。

若 $F_{S,i,t}^T \cdot F_{S,i,t}$ 对每个 (i, t) 均可逆,则式(2)两端同乘以 $(F_{S,i,t}^T F_{S,i,t})^{-1} F_{S,i,t}^T$, 整理得

$$v_{i,t} \approx F_{l,i,t} F_{\Delta,i,t} (\Delta_t - \bar{\Delta}_t) + (S_t - \bar{S}_t) + F_{l,i,t} G_{i,t} n_{i,t}. \quad (3)$$

其中

$$\begin{aligned} v_{i,t} &\equiv F_{l,i,t}(y_{i,t} - \bar{y}_{i,t}), \\ F_{l,i,t} &\equiv (F_{S,i,t}^T F_{S,i,t})^{-1} F_{S,i,t}^T. \end{aligned}$$

若令 $(\bar{\Delta}_t, \bar{S}_t), (\bar{P}_{\Delta,t}, \bar{P}_{S,t})$ 及 $\bar{P}_{\Delta S,t}$ 分别表示 (Δ_t, S_t) 的预测平均值、协方差和互协方差,则可将式(3)改写成如下形式

$$\begin{bmatrix} \hat{\Delta}_t \\ \hat{S}_t \end{bmatrix} = \begin{bmatrix} \bar{\Delta}_t \\ \bar{S}_t \end{bmatrix} + \begin{bmatrix} \bar{P}_{\Delta,t} & \bar{P}_{\Delta S,t} \\ \bar{P}_{S\Delta,t} & \bar{P}_{S,t} \end{bmatrix} \begin{bmatrix} F_{\Delta,i,t}^T F_{l,i,t}^T \\ I \end{bmatrix} E_{i,t}^{-1} v_{i,t}. \quad (4)$$

对应式(4)的卡尔曼滤波为

$$\hat{\Delta}_t = \bar{\Delta}_t + K_{\Delta,i,t} E_{i,t}^{-1} v_{i,t}, \quad (5)$$

$$\hat{P}_{\Delta,t} = P_{\Delta,t} - K_{\Delta,i,t} E_{i,t}^{-1} K_{\Delta,i,t}^T, \quad (6)$$

$$K_{\Delta,i,t} = P_{\Delta,i,t} F_{\Delta,i,t}^T F_{l,i,t}^T + \bar{P}_{\Delta S,t}, \quad (7)$$

$$\begin{aligned} E_{i,t} &= [F_{l,i,t} G_{i,t}^T F_{l,i,t}^T F_{\Delta,i,t}^T + \bar{P}_{S,t} + \\ &\quad F_{l,i,t} F_{\Delta,i,t} P_{\Delta,i,t} F_{\Delta,i,t}^T F_{l,i,t}^T] + \\ &\quad P_{S\Delta,i,t} F_{\Delta,i,t}^T F_{l,i,t}^T + F_{l,i,t} F_{\Delta,i,t} \bar{P}_{\Delta S,t}. \end{aligned} \quad (8)$$

利用 $K(K \geq 2)$ 个传感器观测系统偏差,有近似式

$$E\left[\sum_{i=1}^K C_{i,t}^{-1} v_{i,t} (\Delta_t - \bar{\Delta}_t)^T | \bar{y}_t\right] \approx 0. \quad (9)$$

其中 $C_{i,t} \equiv F_{l,i,t} G_{i,t}^T F_{l,i,t}^T$, 代入式(3)并整理得

$$\sum_{i=1}^K C_{i,t}^{-1} \bar{P}_{S\Delta,t} \approx - \sum_{i=1}^K C_{i,t}^{-1} F_{l,i,t} F_{\Delta,i,t} \bar{P}_{\Delta,t}, \quad (10)$$

因此

$$\bar{P}_{S\Delta,t} \approx - \bar{F}_t \bar{P}_{\Delta,t}. \quad (11)$$

其中 $\bar{F}_t \equiv (\sum_{i=1}^K C_{i,t}^{-1})^{-1} \sum_{i=1}^K (C_{i,t}^{-1} F_{l,i,t} F_{\Delta,i,t})$, 将式(11)代入式(7)(8)得

$$K_{\Delta,i,t} \approx \bar{P}_{\Delta,t} [F_{l,i,t} F_{\Delta,i,t} - \bar{F}_t]^T, \quad (12)$$

$$\begin{aligned} E_{i,t} &\approx C_{i,t} + \bar{P}_{S,t} + F_{l,i,t} F_{\Delta,i,t} \bar{P}_{\Delta,t} F_{\Delta,i,t}^T F_{l,i,t}^T - \\ &\quad \bar{F}_t \bar{P}_{\Delta,t} F_{\Delta,i,t}^T F_{l,i,t}^T - F_{l,i,t} F_{\Delta,i,t} \bar{P}_{\Delta,t} \bar{F}_t. \end{aligned} \quad (13)$$

利用互协方差的近似值代替 $P_{S\Delta,t}$

$$\begin{aligned} E_{i,t} &\approx C_{i,t} + \bar{P}_{S,t} + F_{l,i,t} F_{\Delta,i,t} \bar{P}_{\Delta,t} F_{\Delta,i,t}^T F_{l,i,t}^T - \\ &\quad \bar{F}_t \bar{P}_{\Delta,t} F_{\Delta,i,t}^T F_{l,i,t}^T - F_{l,i,t} F_{\Delta,i,t} \bar{P}_{\Delta,t} \bar{F}_t. \end{aligned}$$

3 偏差估计(Estimation of registration)

为了估计系统偏差,将式(12)代入式(5)、(6)得

$$\hat{\Delta}_t = \bar{\Delta}_t + \bar{P}_{\Delta,t} U_{i,t}, \quad (15)$$

$$\hat{P}_{\Delta,t} = \bar{P}_{\Delta,t} - \bar{P}_{\Delta,t} V_{i,t} \bar{P}_{\Delta,t}^T. \quad (16)$$

其中

$$U_{i,t} \equiv [F_{l,i,t} F_{\Delta,i,t} - \bar{F}_t]^T E_{i,t}^{-1} v_{i,t}, \quad (17)$$

$$V_{i,t} \equiv [F_{l,i,t} F_{\Delta,i,t} - \bar{F}_t]^T E_{i,t}^{-1} [F_{l,i,t} F_{\Delta,i,t} - \bar{F}_t]. \quad (18)$$

假定时变配准偏差状态模型可描述为

$$\Delta_t = a \Delta_{t-1} + (I - a) E(\Delta_0) + w_t. \quad (19)$$

其中 Δ_0 为 $t = 0$ 时的系统偏差, $a = \text{diag}(a_1, \dots, a_K)$, $a_i = \text{diag}(a_{i,\Delta_{i,1}}, a_{i,\Delta_{i,2}}, \dots, a_{i,\Delta_{i,m}})$ 为依传感器的先验信息给定的定常系数, $w_t = \text{col}(w_{1,t}, \dots, w_{m \times K,t})$, $(w_{i,t})$, $i = 1, \dots, m \times K$ 为零均值且相互独立的高斯白噪声序列,因此其协方差满足

$$\text{cov}(w_t) = \text{cov}(\Delta_0) + a \text{cov}(\Delta_0) a^T. \quad (20)$$

则时变配准偏差的预测方程为

$$\bar{\Delta}_t = E(\Delta_t) = E(\Delta_0) + a [\hat{\Delta}_{t-1} - E(\Delta_0)], \quad (21)$$

$$\bar{P}_{\Delta,t} = \text{cov}(\Delta_0) + a [\hat{P}_{\Delta,t-1} + \text{cov}(\Delta_0)] a^T. \quad (22)$$

相应的测量修正方程为:

$$\hat{\Delta}_t \approx \bar{\Delta}_t + \bar{P}_{\Delta,t} \left[\sum_{i=1}^K \sum_{u_i \in (t-1,t]} U_{i,u_i} \right], \quad (23)$$

$$\hat{P}_t \approx \bar{P}_{\Delta,t} - \bar{P}_{\Delta,t} \left[\sum_{i=1}^K \sum_{u_i \in (t-1,t]} V_{i,u_i} \right] \bar{P}_{\Delta,t}^T. \quad (24)$$

其中 u_i 指传感器采样间隔内的某时刻, $U_{i,t}$ 和 $V_{i,t}$ 如式(17)(18).

虽然初始 $E(\Delta_0)$ 可采用离线算法算出^[7], 但经过仿真发现, 初值的选取影响算法的收敛性快慢, 进而影响配准算法的实时性. 为了提高算法的实时性, 本文采用改进的极大似然估计方法^[8], 重新构造如式(25)的初始偏差估计的性能指标函数, 与文献[8]中的性能指标相比, 式(25)描述的性能指标函数只需要很少量的测量数据就能估计偏差, 适合于配准偏差的在线估计和补偿.

$$J = \sum_{i,s} \| y_{i,s,t} - f_{i,s,t}(S_{i,t}, \Delta_{i,t}) \|_{F_{i,s}}^2 + \|\Delta_t - \hat{\Delta}\|_V^2. \quad (25)$$

其中 $\|\cdot\|$ 为矩阵范数, $F_{i,s}$ 是以测量噪声方差为对角线阵的逆矩阵, V 是依据传感器先验信息给定的常数矩阵. 对所有 $S_{i,t}$, 令 $\partial J / \partial S = 0$ 极小化性能指标函数, 再令 $\partial J / \partial \Delta = 0$ 得

$$\Delta = (W + V)^{-1} L. \quad (26)$$

其中,

$$W = \sum_{i,s} (A_{is} - \bar{A}_{is})^T F_{is} (A_{is} - \bar{A}_{is}),$$

$$L = \sum_{i,s} (A_{is} - \bar{A}_{is})^T F_{is} (d_{is} - \bar{d}_{is}) A_{is} = \left. \frac{\partial f_s(\hat{S}_t \Delta_t)}{\partial \Delta_t} \right|_{\Delta=0},$$

$$d_{is} = y_{is} - \hat{y}_{is}.$$

将估计的 Δ_0 代入式(21), 利用式(22)~(24)计算偏差, 并修正测量信息, 跟踪器采用修正后的测量值进行后续滤波、融合等工作.

4 配准算法性能评价 (Performance evaluation for registration)

由统计学理论可知, 无偏估计量 $\hat{\Delta}$ 的协方差阵满足

$$E[(\Delta - \hat{\Delta})(\Delta - \hat{\Delta})^T] \geq J^{-1}. \quad (27)$$

其中 J 为按式(28)定义的 Fisher 信息矩阵

$$J = E\{[\nabla_{\Delta} \log p(Z|\Delta)][\nabla_{\Delta} \log p(Z|\Delta)]^T\} \big|_{\Delta=\hat{\Delta}}. \quad (28)$$

$\bar{\Delta}$ 是偏差 Δ 的真值, $p(Z|\Delta)$ 是似然函数, 将式(28)进一步简化得

$$J = H^T R^{-1} H. \quad (29)$$

其中: $H = [\nabla_{\Delta} f_1^T \quad \nabla_{\Delta} f_2^T \quad \cdots \quad \nabla_{\Delta} f_N^T]^T \big|_{\Delta=\bar{\Delta}}$, N 是测量数据次数, R 是噪声协方差.

$$\text{CRLB}\{[\Delta]_j\} = \{J^{-1}\}_{jj}. \quad (30)$$

式(30)含义指: Fisher 信息矩阵的逆矩阵的对角线元素为配准偏差 Δ 估计的偏差协方差下界[9].

5 仿真结果 (Simulation results)

若多传感器跟踪系统中含有雷达和红外传感器, 假定目标与平台处于同一平面, 不考虑高低角的影响, 假设系统偏差中含有(斜距偏差 $\Delta_{1,r,t}$ 、方位偏差 $\Delta_{i,\theta,t}$, $i = 1, 2$), 即

$$\Delta_{i,t} = [\Delta_{1,r,t} \quad \Delta_{1,\theta,t} \quad \Delta_{2,\theta,t}]^T,$$

$$y_{1,t} = \begin{bmatrix} n_{1,r,t} \\ n_{1,\theta,t} \end{bmatrix} +$$

$$\begin{bmatrix} [(S_{x,t} - d_{1,x})^2 + (S_{y,t} - d_{1,y})^2 + Z_i^2]^{\frac{1}{2}} + \Delta_{1,r,t} \\ \arctg[(S_{y,t} - d_{1,y}) / (S_{x,t} - d_{1,x})] + \Delta_{1,\theta,t} \end{bmatrix},$$

$$y_{2,t} = \begin{bmatrix} n_{2,\theta,t} \end{bmatrix} +$$

$$\begin{bmatrix} \arctg[(S_{y,t} - d_{2,y}) / (S_{x,t} - d_{2,x})] + \Delta_{2,\theta,t} \end{bmatrix}.$$

其中: $S_t = [S_{x,t} \quad S_{y,t}]^T$ 和 $(d_{i,x} \quad d_{i,y})$ 分别表示目标和传感器在直角坐标系下的位置, $[n_{i,t}]$ 是协方差为 $\sigma_{i,\theta}^2$ 和 $\sigma_{i,r}^2$ 的高斯零均值噪声, $i = 1, 2$. 两传感器间的距离为 b . 对于雷达/红外的融合跟踪系统, 根据文献[10]的思想, 二维红外的距离信息可利用融合雷达测量信息和传感器间距离 b 得到, 其中 $\vec{r}_{\text{radar}}$ 为极坐标转换到直角坐标的目标位置矢量.

$$r_{\text{ir}} = r_{\text{radar}} + \frac{\vec{r}_{\text{radar}}^T b}{r_{\text{radar}}}.$$

则在时间间隔 $[t-1, t]$, 可以利用(21)~(24)式计算偏差. 其中

$$\bar{y}_{i,t} = \begin{bmatrix} \bar{r}_{i,t} + \bar{\Delta}_{i,r,t} \\ \bar{\theta}_{i,t} + \bar{\Delta}_{i,\theta,t} \end{bmatrix},$$

$$F_{\Delta,i,t} = \{[F_{\Delta,i,t}]_1 \quad [F_{\Delta,i,t}]_2\},$$

$$[F_{\Delta,i,t}]_i = \begin{bmatrix} -\frac{\mu_{i,t}}{\rho_{i,t}} \cos \theta_{i,t} & -\frac{\mu_{i,t}}{\rho_{i,t}} \sin \theta_{i,t} & 1 & 0 \\ \frac{\sin \theta_{i,t}}{\mu_{i,t}} & -\frac{\cos \theta_{i,t}}{\mu_{i,t}} & 0 & 1 \end{bmatrix},$$

$$F_{S,i,t} = \begin{bmatrix} \frac{\mu_{i,t} \cos \theta_{i,t}}{\rho_{i,t}} & \frac{\mu_{i,t} \sin \theta_{i,t}}{\rho_{i,t}} \\ -\frac{\sin \theta_{i,t}}{\mu_{i,t}} & \frac{\cos \theta_{i,t}}{\mu_{i,t}} \end{bmatrix},$$

$$\theta_{i,t} = \arctg[(S_{y,t} - d_{i,y}) / (S_{x,t} - d_{i,x})],$$

$$\mu_{i,t} = [(S_{x,t} - d_{i,x})^2 + (S_{y,t} - d_{i,y})^2]^{1/2},$$

$$\nabla_{\Delta} f_k^T |_{\Delta=\hat{\Delta}} = \begin{bmatrix} -\cos\theta_{\text{radar}} & -\sin\theta_{\text{radar}} \\ r_{\text{radar}}\sin\theta_{\text{radar}} & -r_{\text{radar}}\cos\theta_{\text{radar}} \\ \cos\theta_{\text{ir}} & \sin\theta_{\text{ir}} \\ r_{\text{ir}}\sin\theta_{\text{ir}} & -r_{\text{ir}}\cos\theta_{\text{ir}} \end{bmatrix},$$

$$R = \begin{bmatrix} \sigma_x^2 & \sigma_{xy}^2 \\ \sigma_{xy}^2 & \sigma_y^2 \end{bmatrix},$$

$$\rho_{i,t} \equiv ((S_{x,t} - d_{i,x})^2 + (S_{y,t} - d_{i,y})^2 + Z_i^2)^{1/2},$$

$$\sigma_x^2 = \sigma_{r_{\text{radar}}}^2 \cos^2 \tilde{\theta}_k^{\text{radar}} + (\tilde{r}_k^{\text{radar}})^2 \sin^2 \tilde{\theta}_k^{\text{radar}} \sigma_{\theta_{\text{radar}}}^2 + \sigma_{r_{\text{ir}}}^2 \cos^2 \tilde{\theta}_k^{\text{ir}} + (\tilde{r}_k^{\text{ir}})^2 \sin^2 \tilde{\theta}_k^{\text{ir}} \sigma_{\theta_{\text{ir}}}^2,$$

$$\sigma_y^2 = \sigma_{r_{\text{radar}}}^2 \sin^2 \tilde{\theta}_k^{\text{radar}} + (\tilde{r}_k^{\text{radar}})^2 \cos^2 \tilde{\theta}_k^{\text{radar}} \sigma_{\theta_{\text{radar}}}^2 + \sigma_{r_{\text{ir}}}^2 \sin^2 \tilde{\theta}_k^{\text{ir}} + (\tilde{r}_k^{\text{ir}})^2 \cos^2 \tilde{\theta}_k^{\text{ir}} \sigma_{\theta_{\text{ir}}}^2,$$

$$\sigma_{xy}^2 = \frac{1}{2} \sin^2(2\tilde{\theta}_k^{\text{radar}}) [\sigma_{r_{\text{radar}}}^2 - (\tilde{r}_k^{\text{radar}})^2 \sigma_{\theta_{\text{radar}}}^2] + \frac{1}{2} \sin^2(2\tilde{\theta}_k^{\text{ir}}) [\sigma_{r_{\text{ir}}}^2 - (\tilde{r}_k^{\text{ir}})^2 \sigma_{\theta_{\text{ir}}}^2].$$

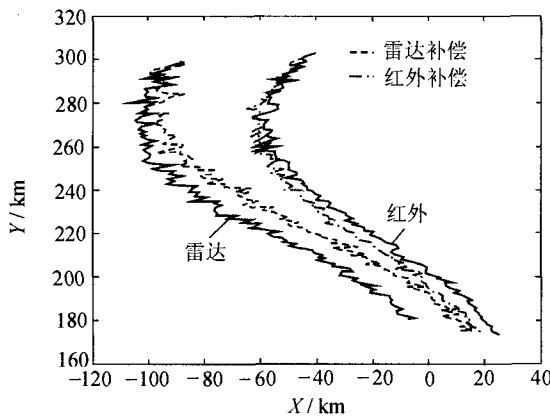


图2 配准后的测量航路

Fig. 2 Compensation trajectory

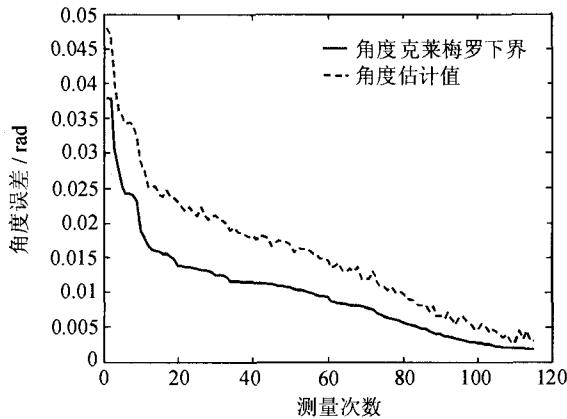


图4 估计的雷达角度偏差误差

Fig. 4 Estimated radar angle bias error

假定目标运动方程为

$$\begin{cases} x_k = 25 - 45\sin(0.03k + 0.698), \\ y_k = 300 - 1.05k. \end{cases}$$

仿真初始条件为:两传感器相距 6 m,传感器的配准偏差为 $\Delta = \{1.8, -0.0875, 0.0526\}$,目标的初始位置为: $(25000 \text{ m}, 300000 \text{ m})$, $\sigma_{1,\theta} = 0.0087 \text{ rad}$, $\sigma_{1,r} = 200 \text{ m}$, $\sigma_{2,\theta} = 0.00175 \text{ rad}$, $a = \text{diag}(a_1, a_2)$, $a_1 = \text{diag}(0.001, 0.001)$, $a_2 = \text{diag}(0.001)$, $y_{i,t} = [y_{i,r,t} \ y_{i,\theta,t}]^T$.

图2为配准后得到的测量航路,图3为雷达距离偏差的估计误差与相应的 Cramer-Rao 下界,图4为雷达角度偏差的估计误差与相应的 Cramer-Rao 下界,图5为红外角度偏差的估计误差与相应的 Cramer-Rao 下界.

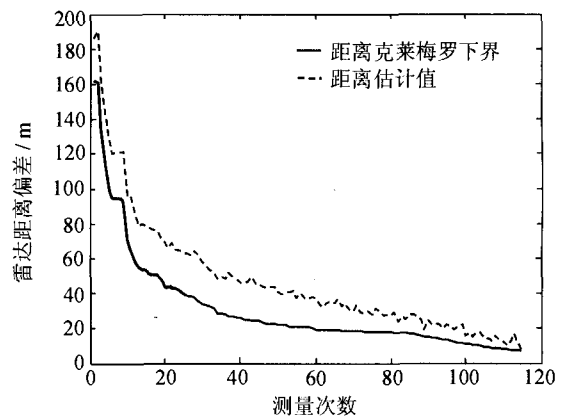


图3 估计的雷达距离偏差误差

Fig. 3 Estimated radar distance bias error

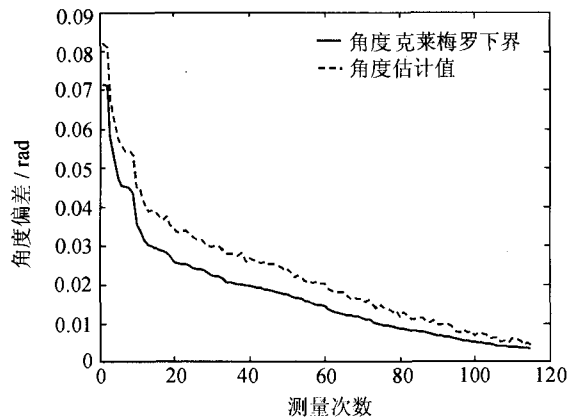


图5 估计的红外角度偏差误差

Fig. 5 Estimated IR angle bias error

6 结论(Conclusion)

本文针对多传感器融合跟踪系统的配准偏差补偿问题,提出了一种在线配准偏差补偿算法.该算法依据多传感器提供的测量和跟踪信息,建立配准偏

差的动态模型,利用极小化似然函数结合卡尔曼滤波方法在线估计系统偏差,补偿和修正跟踪器的测量信息,实现多传感器的融合跟踪.对异类传感器(雷达、红外)组成的多传感器跟踪系统,给出了仿真

结果.从仿真结果可以看出,未经过配准的航路存在偏差,影响到后续融合和跟踪的效果,而经过配准补偿的航路则消除了偏差的影响,提高了融合和跟踪的精度.仿真结果说明了在线补偿算法对系统改善融合跟踪性能的有效性.而对于研究的另一类常见的多传感器纯角度被动融合跟踪系统的在线补偿算法,限于文章篇幅,将另文给出.

参考文献(References):

- [1] BLACKMAN S, POPOLI R. *Design and Analysis of Modern Tracking Systems* [M]. New York: Artech House, 1999.
- [2] FRIEDLAND B. Treatment of bias in recursive filtering [J]. *IEEE Trans on Automatic Control*, 1969, 14(4): 359 - 367.
- [3] ZHOU Y F, LEUNG H, PATRICK C Y. An exact maximum likelihood registration algorithm for data fusion [J]. *IEEE Trans on Aerospace and Electronic Systems*, 1997, 45(6): 1560 - 1572.
- [4] NASSIB N, BISHOP R H. Solution to a multi-sensor tracking problem with sensor registration errors [J]. *IEEE Trans on Aerospace and Electronic Systems*, 1999, 35(1): 354 - 363.
- [5] HELMICK R E, RICE T R. Removal of alignment errors in an integrated system of two 3D sensors [J]. *IEEE Trans on Aerospace and Electronic Systems*, 1993, 29(10): 1333 - 1343.
- [6] HAIM K, HAVA T S. Sensor registration using neural network [J]. *IEEE Trans on Aerospace and Electronic Systems*, 2000, 36(1): 85 - 100.
- [7] MCMICHAEL D W, NOKELLO N. Maximum likelihood registration of dissimilar sensors [C]// *Proc of the First Australian Data Fusion Symposium*. Adelaide: [s. n.], 1996: 31 - 34.
- [8] ZHOU Y F, LEUNG H, BLANQUETTE M. Sensor alignment with earth-centered earth-fixed (ECEF) coordination system [J]. *IEEE Trans on Aerospace and Electronic Systems*, 1999, 35(4): 410 - 417.
- [9] RISTIC B, OKELLO N. Performance bounds for sensor registration [C]// *The Fifth Int Conf of Information Fusion*. Annapolis: [s. n.], 2002: 346 - 353.
- [10] HELMICK R E, RICE T R. Alignment of a 2-D sensor and 3-D radar [J]. *Acquisition, Tracking, and Pointing VI*, 1992, 1697(3): 142 - 155.

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- [7] LUENBERGER D G, ARBEL A. Singular dynamical Leontief systems [J]. *Econometrica*, 1977, 45(4): 991 - 995.
- [8] COBB D. Controllability, observability, and duality in singular systems [J]. *IEEE Trans on Automatic Control*, 1984, 29(11): 1076 - 1082.
- [9] FRIDMAN E. Stability of linear descriptor systems with delay: a Lyapunov-based approach [J]. *J of Mathematical Analysis and Applications*, 2002, 273(1): 24 - 44.
- [10] XU S Y, DOOREN P V, STETAN R, et al. Robust stability and stabilization for singular systems with state delay and parameter uncertainty [J]. *IEEE Trans on Automatic Control*, 2002, 47(7): 1122 - 1128.
- [11] FRIDMAN E, SHAKED U. H_∞ -control of linear state - delay descriptor systems: an LMI approach [J]. *Linear Algebra and its Applications*, 2002, 351 - 352: 271 - 302.
- [12] 王汝凉, 李远清, 刘永清. 离散滞后广义系统稳定域的定量估计[J]. 控制理论与应用, 2002, 19(2): 188 - 192.
(WANG Ruliang, LI Yuanqing, LIU Yongqing. A quantitative estimate on the stability region of discrete-delay singular systems [J]. *Control Theory & Applications*, 2002, 19(2): 188 - 192.)
- [13] 谢湘生, 胡刚, 刘洪伟. 带有外干扰的滞后离散广义系统鲁棒 H_∞ 控制器设计: LMI 方法[J]. 控制理论与应用, 2002, 19(6): 937 - 939.
(XIE Xiangsheng, HU Gang, LIU Hongwei. Robust H_∞ control of discrete-time singular systems with exogenous disturbance and time-delays [J]. *Control Theory & Applications*, 2002, 19(6): 937 - 939.)
- [14] XU S Y, LAM J, YANG C W. Robust H_∞ control for discrete singular systems with state delay and parameter uncertainty [J]. *Dynamics of Continuous, Discrete and Impulsive Systems*, 2002, 9b(4): 539 - 554.

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