

Robust Integrated Navigation of a Low Cost System

Saman M. Siddiqui, Fang Jiancheng

Abstract—Robust nonlinear integrated navigation of GPS and low cost MEMS is a hot topic of research these days. A robust filter is required to cope up with the problem of unpredictable discontinuities and colored noises associated with low cost sensors. H_∞ filter is previously used in Extended Kalman filter and Unscented Kalman filter frame. Unscented Kalman filter has a problem of Cholesky matrix factorization at each step which is a very unstable operation. To avoid this problem in this research H_∞ filter is designed in Square root Unscented filter framework and found 50% more robust towards increased level of colored noises.

Keywords— H_∞ filter, MEMS, GPS, Nonlinear system, robust system, Square root unscented filter.

I. INTRODUCTION

THIS research designs a robust stable filter tolerant towards increased levels of non white Gaussian noises. The most popular approaches of nonlinear filtering i.e., Kalman filter (KF) and Unscented Kalman filter (UKF) have been utilized in H_∞ filter framework in [1] using game theory approach. The results with UKF H_∞ were found better than EKF H_∞ as UKF is more robust with initial condition errors and gives 3rd to 4th order of accuracy with nonlinear system. On the other hand the UKF needs Cholesky matrix factorization of all covariance matrices which requires these to be positive definite at each time step. Sometimes this condition is violated when noises are non Gaussian and colored, to resolve this problem Square root unscented filter (SRUKF) was developed in [2] by utilizing three methods of linear algebra. This filter is so far the most stable form of UKF. In this paper H_∞ filter is utilized in SRUKF frame to increase robustness margins [3] and called SRUKF H_∞ .

II. H_∞ UKF AND H_∞ SRUKF FILTERS

H_∞ UKF filters are described in [4]. Reference [4] utilized modified recursive Riccati equation to incorporate H_∞ norm bound in standard UKF set up described in [5]. The new state and covariance update equation in UKF set up can be given as (1)-(2).

$$P_k = P_{k-1} - [P_{X_k Y_k} \quad P_{k-1}] \begin{bmatrix} P_{Y_k} + I & P_{X_k Y_k}^T \\ P_{X_k Y_k} & P_{k-1} - \gamma^2 I \end{bmatrix}^{-1} [P_{X_k Y_k} \quad P_{k-1}]^T \quad (1)$$

$$X_k = X_{k|k-1} + P_{X_k Y_k} (R + P_{Y_k})^{-1} (Y_k - Y_{k|k-1}) \quad (2)$$

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Here P_k and P_{k-1} is system covariance matrix. $P_{X_k Y_k}$ is cross covariance matrix of measurement and state. γ is the designer selected value for bounded variance. This modification gives significant improvement in the presence of colored noise. For H_∞ filter, as in [4] the condition in (3) must hold:

$$P_k^{-1} = P_{k-1}^{-1} + H_k^T R^{-1} H_k - \gamma_k^{-2} I > 0 \quad (3)$$

Here H_k is the observation mapping matrix and R is measurement covariance matrix, so we can choose γ for UKF H_∞ Filter as in (4):

$$\gamma_k^2 = \alpha_{\max} [\text{eig}(P_{k-1}^{-1} + P_{k-1}^{-1} P_{X_k Y_k} R^{-1} (P_{k-1}^{-1} P_{X_k Y_k})^T)^{-1}] \quad (4)$$

Here γ should be greater than 1. To apply robust recursive Riccati equations in Square root unscented filter set up, this research has used (5)-(8).

Square root of $P_{X_k Y_k}$ can be given as in (5):

$$S_{xyk} = S_{xk} H_k^T \quad (5)$$

And U can be calculated as in (6):

$$U = \begin{bmatrix} S_{xyk} & S_{xk} \end{bmatrix} \begin{bmatrix} S_{yk} & S_{xyk}^T \\ S_{xyk} & -\gamma S_k + S_{xk} \end{bmatrix}^{-1} \begin{bmatrix} S_{xyk} & S_{xk} \end{bmatrix}^T \quad (6)$$

Here S_k is the scaling matrix. The rest of the calculation of SRUKF remains same as described in [2]. To ensure stability the factor γ can be given as in (7):

$$\gamma_k^2 = \alpha \max [\text{eig}((S_{xk} * S_{xk}^T)^{-1} + H_k^T R^{-1} H_k)^{-1}] \quad (7)$$

III. RESULTS AND DISCUSSION

A trajectory with bigger (low dynamic loops) and smaller (high dynamic loops) is generated with 6Dof software. The signals are corrupted using colored noises generated through (8):

$$\eta_{AR} = -1.5\eta_{AR}(t-1) - 0.75\eta_{AR}(t-2) - 0.125\eta_{AR}(t-3) + w + 0.5 \quad (8)$$

The level of noise is selected by multiplying signal to noise ratio of white noise w as 10,20,30,40,50. These values are added into values of accelerometer and gyro data at each time step. The different parameter values can be given as:

$$x_k = [\delta\dot{r}, \delta\dot{v}, \delta\dot{q}, \delta\dot{a}_{acc}, \delta\dot{a}_{gyr}]$$

$$P_k = \text{diag}[(4)^2, (4)^2, (4)^2, (4)^2, (4)^2, (0.5)^2, (0.5)^2, (0.5)^2, (0.5)^2, (9.81e^{-3})^2, (9.81e^{-3})^2, (9.81e^{-3})^2, (2.4241e^{-5})^2, (2.4241e^{-5})^2, (2.4241e^{-5})^2, \dots]$$

$$Q_k = \text{diag}[1e^{-6}, 1e^{-6}, 1e^{-6}, 1e^{-13}, 1e^{-13}, 1e^{-13}, \dots]$$

$$R_k = \text{diag}[(2)^2, (2)^2, (2)^2, (2)^2, (2)^2, (2)^2]$$

$$\alpha_{\max} = 1.1342$$

$$S_k = \text{diag}[0.5, 0.5, 0.5, 0.7, 0.7, 1, 1, 0.5, 0.5, 1, 4, 1, 1, 10, 1, 1]$$

$$\alpha = 0.01, \beta = 2, \kappa = 3 - n$$

Here x_k is the state vector and all the rest are tuning parameter of filter as in [2] and [4]. The new filter SRUKFH ∞ results are compared with UKFH ∞ results with up to 5 times noise levels. Later is found more robust, whereas former diverged. Fig. 1 shows this result. Fig. 2 shows performance of two filters in the presence of GPS outage of two minutes at different interval. The system state vector is composed of 16 parameters, three positions in local frame, three velocities, four quaternion, and six random biases of accelerometer and gyro.

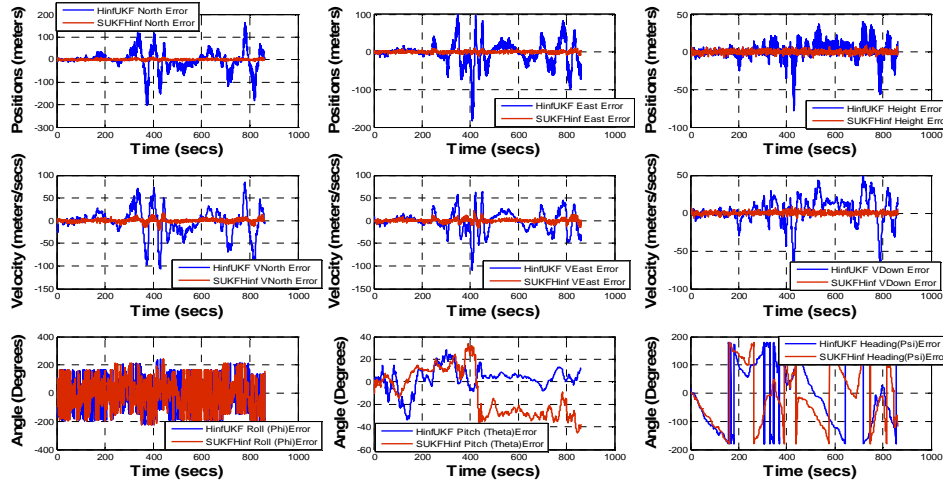


Fig. 1 UKFH ∞ / SRUKFH ∞ performance with 5x noises

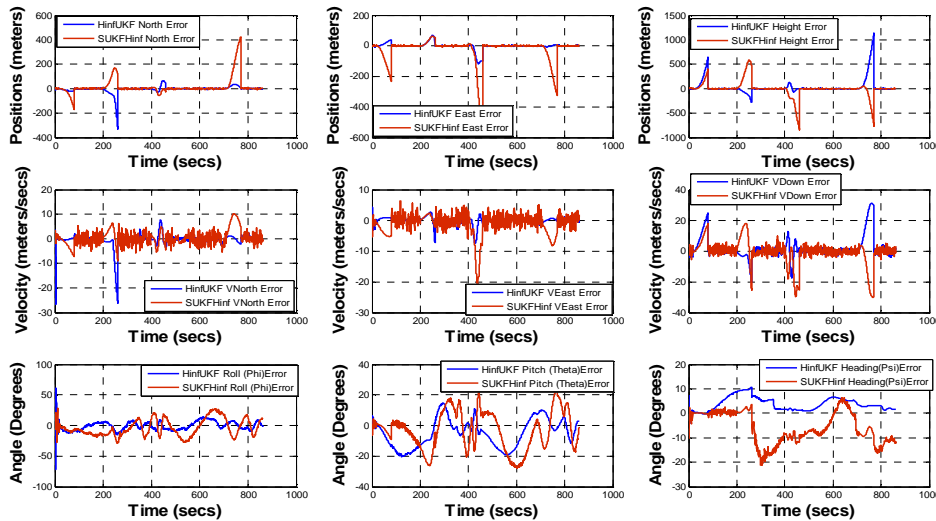


Fig. 2 UKFH ∞ / SRUKFH ∞ performance with GPS outage

A Monte Carlo analysis was made with increased level of noises with both UKFH ∞ and SRUKFH ∞ . The system simulated is composed of commercial grade MEMS IMU and a GPS receiver of moderated accuracy whose data is

available at a rate of 1Hz with frequent outages. The accuracy of gyro and accelerometer is 5°/hr and 1mg respectively. The mechanization equation of this system can be given in [6].

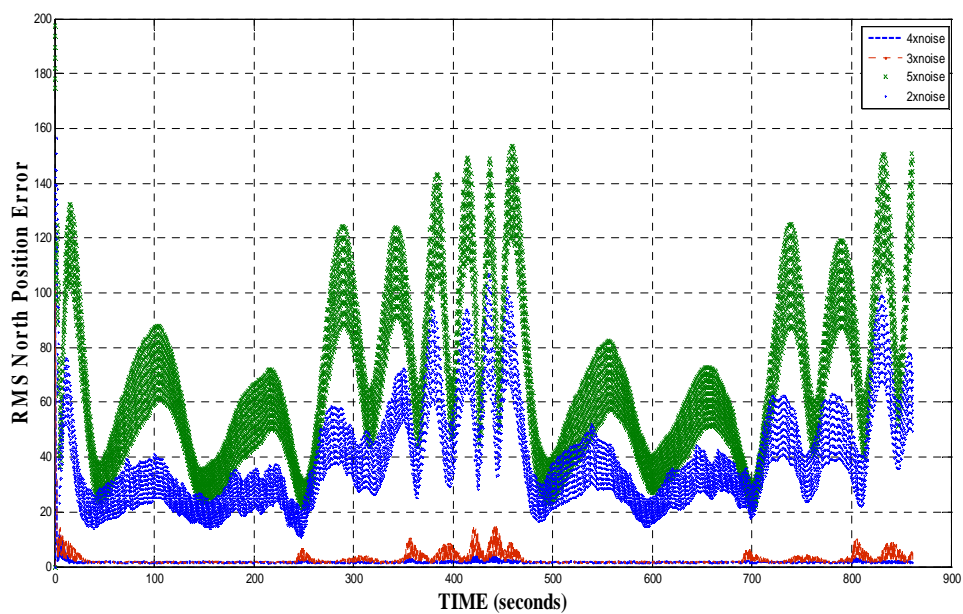


Fig. 3 UKFH ∞ performance with 100 runs of Monte Carlo simulations in presence of different level of noises

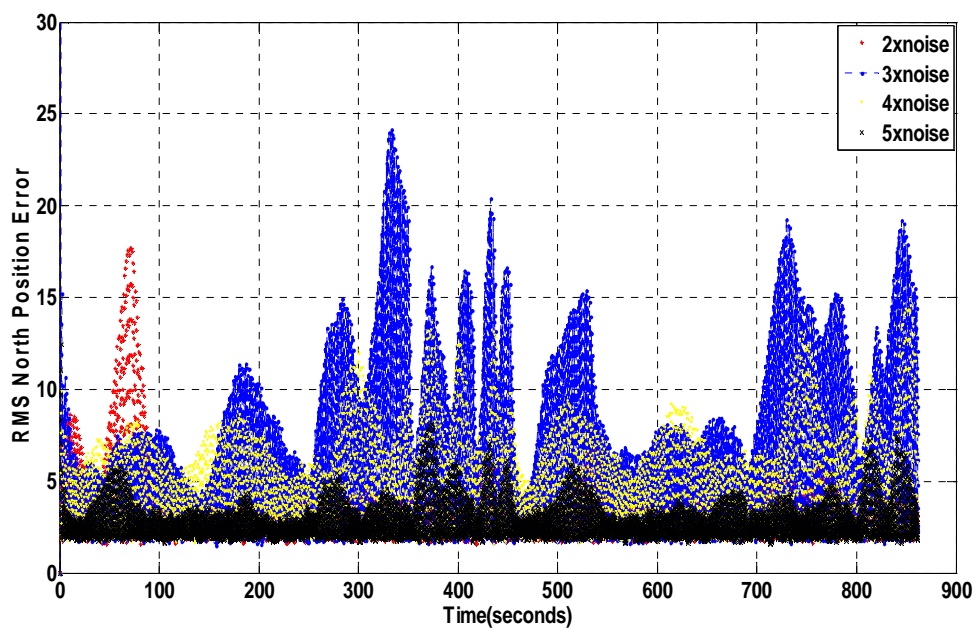


Fig. 4 SRUKFH ∞ performance with 100 runs of Monte Carlo simulations in presence of different level of noises

Fig. 3 and Fig.4 show the results.. The result clearly shows that SRUKFH ∞ are better and more stable towards increased level of noises and computation time is also relatively less than former approach. Table I summarizes these results.

TABLE I
COMPARISON OF H ∞ SRUKF AND H ∞ UKF

| Noise level | H ∞ SRUKF | | H ∞ UKF | |
|-------------|------------------|-------|----------------|-------|
| | CPU Time | STD | CPU Time | STD |
| 0.01 | ~29sec | 3.59 | ~31sec | 3.532 |
| 0.03 | ~29sec | 4.941 | ~31sec | 3.913 |
| 0.09 | ~29sec | 3.934 | ~31sec | 17.61 |
| 0.3 | ~29sec | 3.387 | ~31sec | 29.71 |

IV. CONCLUSION

This study showed that as SRUKFH ∞ is the most stable form of UKF filters, with lower level of noises it performed equally well as UKFH ∞ but as the noise levels increased its performance remain consistent and the former filter started diverging and some simulations stopped due to violation of condition of positive definitiveness of covariance matrices. On the other hand in GPS outages UKFH ∞ was better than new filter. Further work can be done to improve the computation complexity by using any switching technique.

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REFERENCES

- [1] S. M. Siddiqui, F Jiancheng, "Navigation and self alignment of inertial systems using nonlinear H ∞ filters", *In Proc. of WASET*, Paris, 2011.
- [2] Rudolph van der Merwe, Eric A Wan, "The square root unscented filter for parameter and state estimation", *IEEE Proc. of the international conference on Acoustics, speech and signal processing*, 2001, vol. 6, pp 3461-3464
- [3] S. M. Siddiqui, F Jiancheng, "Design of a hybrid non linear H ∞ filter for a low cost airborne vehicle based on low/high dynamic switching", *Journal of Aerospace Science & Technology*, submitted for publication
- [4] Wenling Li, Yingmi Jia, "H ∞ filter Filtering for a class of nonlinear discrete time systems based on unscented transform", *journal of Signal processing*, vol. 90, no. 1, 2010, pp 3301-3307.
- [5] S.J.Julier and J.K.Uhlmann, "Unscented filtering and nonlinear estimation", in *Proc. IEEE*, vol.92, Mar. 2004, pp.401-442.
- [6] Adriano Solimeno, Low cost INS/GPS Data fusion with EKF for airborne applications, University of Lisbon MS thesis, July 2007.