Application of the sliding innovation filter to complex road

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ABSTRACT

The sliding innovation filter (SIF) is a newly developed filter that may be applied to both linear and non-linear systems. The SIF shares similar principles with sliding mode observers (SMO) and other variable structure filters such as the smooth variable structure filter (SVSF). The SIF utilizes the true trajectory as a hyperplane and forces the estimates to stay within a region of the hyperplane through the use of a discontinuous correction gain. In this paper, the SIF is applied to the well-known complex road estimation problem with nonlinear system function. The results of the application are compared with the SVSF, and future work is discussed.

Keywords: Complex road, maneuvering, SIF, SVSF, performance.

1. INTRODUCTION

Sliding Innovation Filter (SIF) is a newly developed filter that was proposed in 2020 [1-7]. The filter is a model-based filter [8-15] that uses the same principle of sliding mode observer [16-39] and smooth variable structure filter [40-51]. The filter uses the actual trajectory as hyperplane and forces the estimates to remain in its neighborhood using a corrective gain that is developed from Lyapunov theorem. The filter is considered stable and robust against disturbances and uncertainties. If the filter is combined with controller, the system performance is improved [52-62].

SIF has simple structure and is considered efficient. It can be easily modified or combined with other filters to improve its performance in terms of optimality and extracting the hidden states [63-67]. In this work, the filter is used to estimate vehicle trajectories while it is maneuvering in 2D plane. This paper is organized as follows: The SIF and the proposed method are introduced in Section 2. Section 3 discuss the application of the proposed method to a third order system. Section 4 concludes the paper and hint on the future works.

2. METHODOLOGY

2.1. System under study

In this paper, a complex maneuvering system is considered where a vehicle moves at different velocities and different shapes in x-y plane. Both filters; SVSF and SIF are tested on this system and then the results are compared. The maneuvering model is considered nonlinear system as the relations are not linear and it involves with sinusoidal signals. The system has five states, including the positions on the x- and y- axes, x_1 and x_2, respectively, the velocities on both axes, x_3 and x_4, respectively, and the maneuvering rotational angle, x_5. All the states are assumed to be measured. The discrete form of the model is defined below through equations (1) to (14), including the sensors' equations.

$$x_{1,k+1} = x_{1,k} + M\, x_{3,k} + N\, x_{4,k} + w_{1,k} \tag{1}$$
$$x_{2,k+1} = x_{2,k} + N\, x_{3,k} + M\, x_{4,k} + w_{2,k} \tag{2}$$
$$x_{3,k+1} = C\, x_{3,k} - S\, x_{4,k} + w_{3,k} \tag{3}$$
$$x_{4,k+1} = S\, x_{3,k} + C\, x_{4,k} + w_{4,k} \tag{4}$$
$$x_{5,k+1} = x_{5,k} + w_{5,k} \tag{5}$$
$$z_{1,k+1} = x_{1,k+1} + v_{2,k+1} \tag{6}$$
$$z_{2,k+1} = x_{2,k+1} + v_{2,k+1} \tag{7}$$

Signal Processing, Sensor/Information Fusion, and Target Recognition XXXI, edited by Ivan Kadar, Erik P. Blasch, Lynne L. Grewe, Proc. of SPIE Vol. 12122, 121220A · © 2022 SPIE · 0277-786X · doi: 10.1117/12.2619571

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$$z_{3,k+1} = x_{3,k+1} + v_{3,k+1} \quad (8)$$

$$z_{4,k+1} = x_{4,k+1} + v_{4,k+1} \quad (9)$$

$$z_{5,k+1} = x_{5,k+1} + v_{5,k+1} \quad (10)$$

Where w and v are the system and measurement noise vectors. M and N are defined as:

$$M = S/x_{5,k} \quad (11)$$

$$N = (1 - C)/x_{5,k} \quad (12)$$

And S and C are defined as:

$$S = sin(x_{5,k}) \quad (13)$$

$$C = cos(x_{5,k}) \quad (14)$$

2.2. Smooth Variable Structure Filter

In this section, the SVSF is derived as a non-matrix form to solve the model in section 2.1. The SVSF consists of two steps:

1- **Prediction Stage**, where the a priori estimate and its measurement, $\hat{x}_{k+1|k}$ and $\hat{z}_{k+1|k}$, respectively, are calculated using the following equations:

$$\hat{x}_{1,k+1|k} = \hat{x}_{1,k|k} + \widehat{M}\,\hat{x}_{3,k|k} + \widehat{N}\,\hat{x}_{4,k|k} \quad (15)$$

$$\hat{x}_{2,k+1|k} = \hat{x}_{2,k|k} + \widehat{N}\,\hat{x}_{3,k|k} + \widehat{M}\,\hat{x}_{4,k|k} \quad (16)$$

$$\hat{x}_{3,k+1|k} = \hat{C}\,\hat{x}_{3,k|k} - \hat{S}\,\hat{x}_{4,k|k} \quad (17)$$

$$\hat{x}_{4,k+1|k} = \hat{S}\,\hat{x}_{3,k|k} + \hat{C}\,\hat{x}_{4,k|k} \quad (18)$$

$$\hat{x}_{5,k+1|k} = \hat{x}_{5,k|k} \quad (19)$$

$$\hat{z}_{1,k+1|k} = \hat{x}_{1,k+1|k} \quad (20)$$

$$\hat{z}_{2,k+1|k} = \hat{x}_{2,k+1|k} \quad (21)$$

$$\hat{z}_{3,k+1|k} = \hat{x}_{3,k+1|k} \quad (22)$$

$$\hat{z}_{4,k+1|k} = \hat{x}_{4,k+1|k} \quad (23)$$

$$\hat{z}_{5,k+1|k} = \hat{x}_{5,k+1|k} \quad (24)$$

Where $\widehat{M}$ and $\widehat{N}$ are defined as:

$$\widehat{M} = \hat{S}/\hat{x}_{5,k|k} \quad (25)$$

$$\widehat{N} = (1 - \hat{C})/\hat{x}_{5,k|k} \quad (26)$$

And $\hat{S}$ and $\hat{C}$ are defined as:

$$\hat{S} = \sin(\hat{x}_{5,k|k}) \tag{27}$$
$$\hat{C} = \cos(\hat{x}_{5,k|k}) \tag{28}$$

2- **Update/Correction Stage**, where the a posteriori estimate and its measurements, $\hat{x}_{\mathrm{k+1|k+1}}$ and $\hat{z}_{k+1|k+1}$, respectively, are calculated using the following equations

a. Calculating the a priori estimation error

$$\mathbf{e}_{1,k+1|k} = z_{1,k+1} - \hat{z}_{1,k+1|k} \tag{29}$$
$$\mathbf{e}_{2,k+1|k} = z_{2,k+1} - \hat{z}_{2,k+1|k} \tag{30}$$
$$\mathbf{e}_{3,k+1|k} = z_{3,k+1} - \hat{z}_{3,k+1|k} \tag{31}$$
$$\mathbf{e}_{4,k+1|k} = z_{4,k+1} - \hat{z}_{4,k+1|k} \tag{32}$$
$$\mathbf{e}_{5,k+1|k} = z_{5,k+1} - \hat{z}_{5,k+1|k} \tag{33}$$

b. Calculating the correction gain

$$\mathbf{K}_1 = \left(\left|e_{1,k+1|k}\right| + \gamma\left|e_{1,k|k}\right|\right)sat\left(e_{1,k+1|k}, \Psi_1\right) \tag{34}$$
$$\mathbf{K}_2 = \left(\left|e_{2,k+1|k}\right| + \gamma\left|e_{2,k|k}\right|\right)sat\left(e_{2,k+1|k}, \Psi_2\right) \tag{35}$$
$$\mathbf{K}_3 = \left(\left|e_{3,k+1|k}\right| + \gamma\left|e_{3,k|k}\right|\right)sat\left(e_{3,k+1|k}, \Psi_3\right) \tag{36}$$
$$\mathbf{K}_4 = \left(\left|e_{4,k+1|k}\right| + \gamma\left|e_{4,k|k}\right|\right)sat\left(e_{4,k+1|k}, \Psi_4\right) \tag{37}$$
$$\mathbf{K}_5 = \left(\left|e_{5,k+1|k}\right| + \gamma\left|e_{5,k|k}\right|\right)sat\left(e_{5,k+1|k}, \Psi_5\right) \tag{38}$$

c. Calculating the a posteriori estimates and their measurements

$$x_{1,k+1|k+1} = x_{1,k+1|k} + \mathbf{K}_1 \tag{39}$$
$$x_{2,k+1|k+1} = x_{2,k+1|k} + \mathbf{K}_2 \tag{40}$$
$$x_{3,k+1|k+1} = x_{3,k+1|k} + \mathbf{K}_3 \tag{41}$$
$$x_{4,k+1|k+1} = x_{4,k+1|k} + \mathbf{K}_4 \tag{42}$$
$$x_{5,k+1|k+1} = x_{5,k+1|k} + \mathbf{K}_5 \tag{43}$$

$$\hat{z}_{1,k+1|k+1} = \hat{x}_{1,k+1|k+1} \tag{44}$$
$$\hat{z}_{2,k+1|k+1} = \hat{x}_{2,k+1+k+1} \tag{45}$$
$$\hat{z}_{3,k+1|k+1} = \hat{x}_{3,k+1|k+1} \tag{46}$$
$$\hat{z}_{4,k+1|k+1} = \hat{x}_{4,k+1+k+1} \tag{47}$$
$$\hat{z}_{5,k+1|k+1} = \hat{x}_{5,k+1|k+1} \tag{48}$$

d. Calculating the a posteriori estimation error, $e_{k+1|k+1}$

$$\mathbf{e}_{1,k+1|k+1} = z_{1,k+1} - \hat{z}_{1,k+1|k+1} \tag{49}$$
$$\mathbf{e}_{2,k+1|k+1} = z_{2,k+1} - \hat{z}_{2,k+1|k+1} \tag{50}$$
$$\mathbf{e}_{3,k+1|k+1} = z_{3,k+1} - \hat{z}_{3,k+1|k+1} \tag{51}$$
$$\mathbf{e}_{4,k+1|k+1} = z_{4,k+1} - \hat{z}_{4,k+1|k+1} \tag{52}$$
$$\mathbf{e}_{5,k+1|k+1} = z_{5,k+1} - \hat{z}_{5,k+1|k+1} \tag{53}$$

2.3. Sliding Innovation Filter

In this section, the SIF is derived as a non-matrix form to solve the model in section 2.1. The SIF consists of two steps:

1- **Prediction Stage**, where the a priori estimate and its measurement, $\hat{x}_{k+1|k}$ and $\hat{z}_{k+1|k}$, respectively, are calculated using the equations (15) to (28).

2- **Update/Correction Stage**, where the a posteriori estimate and its measurements, $\hat{x}_{\mathrm{k+1|k+1}}$ and $\hat{z}_{k+1|k+1}$, respectively, are calculated using the following equations

a. Calculating the a priori estimation error

$$\mathbf{e}_{1,k+1|k} = z_{1,k+1} - \hat{z}_{1,k+1|k} \quad (54)$$
$$\mathbf{e}_{2,k+1|k} = z_{2,k+1} - \hat{z}_{2,k+1|k} \quad (55)$$
$$\mathbf{e}_{3,k+1|k} = z_{3,k+1} - \hat{z}_{3,k+1|k} \quad (56)$$
$$\mathbf{e}_{4,k+1|k} = z_{4,k+1} - \hat{z}_{4,k+1|k} \quad (57)$$
$$\mathbf{e}_{5,k+1|k} = z_{5,k+1} - \hat{z}_{5,k+1|k} \quad (58)$$

b. Calculating the correction gain

$$\mathbf{K}_1 = e_{1,k+1|k} sat\left(\left|e_{1,k+1|k}\right|, \Psi_1\right) \quad (59)$$
$$\mathbf{K}_2 = e_{2,k+1|k} sat\left(\left|e_{2,k+1|k}\right|, \Psi_2\right) \quad (60)$$
$$\mathbf{K}_3 = e_{3,k+1|k} sat\left(\left|e_{3,k+1|k}\right|, \Psi_3\right) \quad (61)$$
$$\mathbf{K}_4 = e_{4,k+1|k} sat\left(\left|e_{4,k+1|k}\right|, \Psi_4\right) \quad (62)$$
$$\mathbf{K}_5 = e_{5,k+1|k} sat\left(\left|e_{5,k+1|k}\right|, \Psi_5\right) \quad (63)$$

c. Calculating the a posteriori estimates and their measurements

$$x_{1,k+1|k+1} = x_{1,k+1|k} + \mathbf{K}_1 \quad (64)$$
$$x_{2,k+1|k+1} = x_{2,k+1|k} + \mathbf{K}_2 \quad (65)$$
$$x_{3,k+1|k+1} = x_{3,k+1|k} + \mathbf{K}_3 \quad (66)$$
$$x_{4,k+1|k+1} = x_{4,k+1|k} + \mathbf{K}_4 \quad (67)$$
$$x_{5,k+1|k+1} = x_{5,k+1|k} + \mathbf{K}_5 \quad (68)$$

3. RESULTS AND DISCUSSION

In this work, the SVSF and SIF are applied to the maneuvering system of section 2.1. Fig. 1, Fig. 2 and Fig. 3 show the results for the vehicle positions, velocities and maneuvering rotational angle. The results are compared in two terms: the root mean squared error (RMSE) and the maximum absolute value of the error, using the following equations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{ns}\left(x_{Actual,i} - x_{Prediction,i}\right)^2}{ns}} \quad (69)$$

$$MAE = \max(|x_{Actual} - x_{Prediction}|) \quad (70)$$

The RMSE and MAE are listed in table 1 and table 2, respectively. The results show that both SVSF and SIF have a good estimation for the states. Moreover, the results show that SIF has a slightly better performance compare to SVSF, where it has 0.5% less RMSE and better estimation for the fifth state in term of MAE. Moreover, the SIF has a structure that is simpler than the structure of SVSF and does not need a memory.

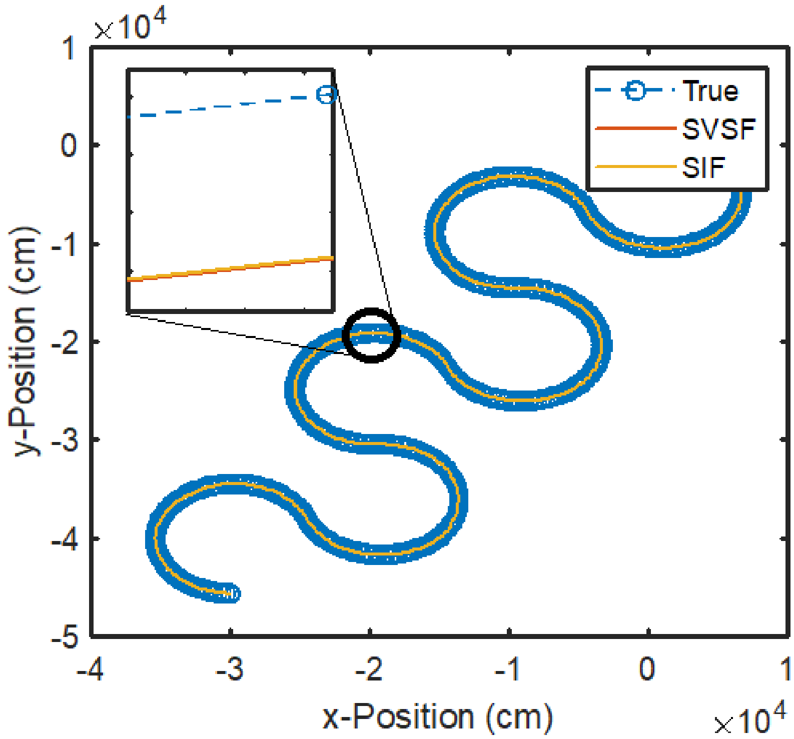

Fig. 1. The estimation of the position in x-y plane for SVSF and SIF

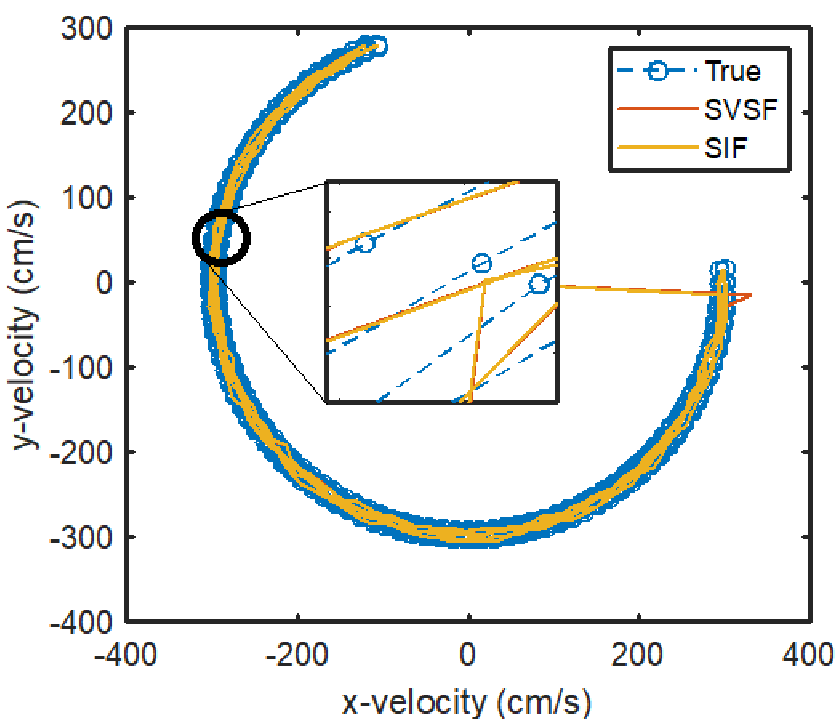

Fig. 2. The estimation of the velocity in x-y plane for SVSF and SIF

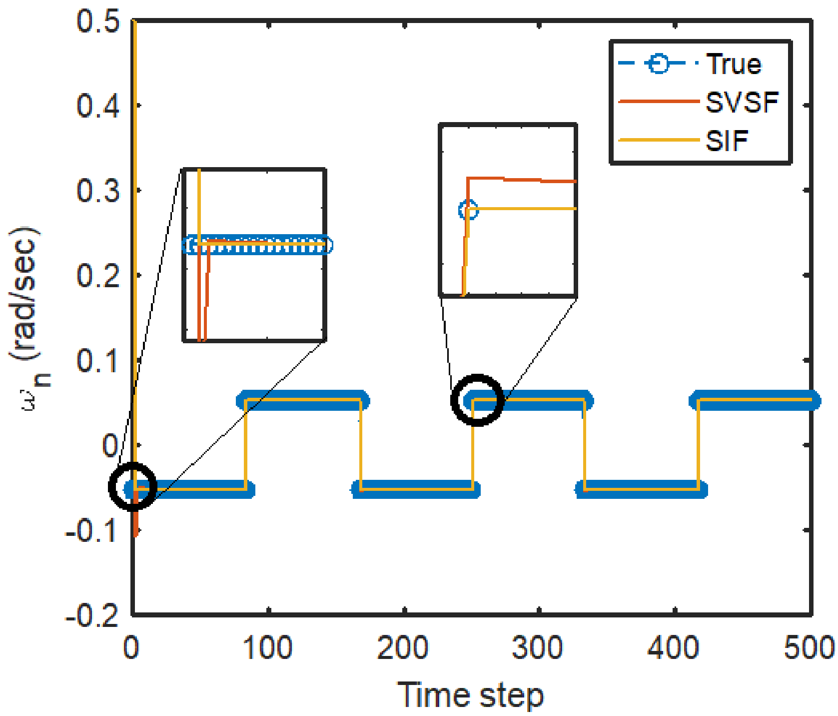

Fig. 3. Estimation of the fifth state for SVSF and SIF

Table 1. RMSE of the simulated results

	RMSE in				
	$x_1\ (cm)$	$x_3(cm/s)$	$x_2(cm)$	$x_4(cm/s)$	$x_5(rad/s)$
SVSF	18.7818	13.5279	30.3701	1.3798	0.024827
SIF	18.6895	13.4552	30.2192	1.3749	0.024702

Table 2. MAE of the simulated results

	MAE in				
	$x_1\ (cm)$	$x_3(cm/s)$	$x_2(cm)$	$x_4(cm/s)$	$x_5(rad/s)$
SVSF	414.94	299.2	674.8	5.17775	0.5524
SIF	414.96	299.2	674.8	5.16775	0.5524
SVSF without initial error	11.4	4.203	7.629	5.178	1.5×10^{-3}
SIF without initial error	11.4	4.188	7.623	5.168	3.5×10^{-17}

4. CONCLUSION

In this article, the SVSF and SIF are used to estimate vehicle trajectories, velocities and maneuvering rotational speed. The results show that both filters performance well on the system with slightly superior performance to the SIF, where the results are improved 0.5% in term RMSE and significantly large improvement for the maneuvering rotational speed in term of MAE. For future work, the filters will be tested using an experimental setup and the results will be compared to other state of art filters.

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