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Analytical Bounds for an Interval Kalman Filter

Quoc-Hung Lu\textsuperscript{1}, Soheib Fergani\textsuperscript{1}, Carine Jauberthie\textsuperscript{1}

Abstract—This paper is concerned with analytical developments of results firstly introduced by the authors in [1]. These developments are devoted to the optimization of upper bounds of the interval Kalman Filter [2]. The proposed study is mainly highlighted through two aspects. Firstly, the optimization is further performed by considering a class of upper bounds and minimizing the traces of these bounds in two stages (in terms of a gain matrix and then with respect to a scalar parameter). Secondly, the paper provides conditions under which the optimal trace value is controlled and hence the proposed Algorithm in [1], namely Optimal Upper Bound Interval Kalman Filter (OUBIKF), is ensured to perform with stability (i.e. without width explosion of the resulting interval estimators). Also under these conditions, the OUBIKF Algorithm, having a similar structure of the Standard Kalman Filter (SKF), is ensured to get a smaller trace upper bound of the covariance matrices in the correction step than the one in the prediction step. Numerical simulations based on an automotive model is performed to illustrate the developed results.

I. INTRODUCTION

With the growth of the industrial automatization and the fast development of intelligent system applications, the necessity of efficient control strategies have risen to higher levels. Nevertheless, the main problems to the synthesis of such solutions have been the cost and the feasibility. Indeed, all efficient control approaches are based on reliable information either from high precision sensors (expensive and not always easy to embed) or high fidelity information reconstruction (estimators, observers). For this sake, in both industry and academia, Kalman Filter introduced in [3] has always been interested by its elegant form and result characteristics (optimal estimator, on-line implementation,...). This is a kind of stochastic approach for estimation and referred as Standard Kalman Filter (SKF). Since then, many extensions of the SKF have been presented to improve its applicability and performance when dealing additionally with bounded uncertainties, of which the two major derivations are robust and interval Kalman filtering.

The robust Kalman filtering, [4]–[7], provides essentially point estimators (of the real states) attempting to limit the disturbance effects to the filter performance. For instance, in [6] and [7], finite-horizon robust Kalman filters for discrete time-varying uncertain systems with additive uncertain covariance white noises are studied without and with missing measurements respectively. Both papers concern a minimization of the trace of a chosen upper bound of all admissible error estimation covariances with respect to (w.r.t.) some design scalar parameters selected (or tuned) adequately, says a pointwise optimization approach.

The interval Kalman filtering provides essentially intervals containing all admissible estimators (of the real states) consistent with considered uncertainties and usually being used as interval estimators for bounds of the real states. It may have a relation with the robust approach when using an element (usually the center) of the yielded interval as a robust estimator in some sense to be precised, however this is not the initial objective of the interval approach. The Interval Kalman Filter (IKF) was first introduced in [2] with an optimal solution and a suboptimal scheme for the purpose of real-time implementation. Then, authors have tried to further investigate this interesting research by its simplicity (although with conservatism) in computation thanks to interval computations (Section II-A) and the similar structure of the SKF with two steps (prediction and correction) in which the later would improve the estimator obtained from the former via the stake of a gain matrix [1], [8], [9].

[8] and [9] study enhancing methods for IKF and [1] proposes an optimal solution for the conservatism problem due to the choice of the IKF bounds. In [8], the proposed method consists in adding some positivity constraints together with the SIVIA algorithm to obtain the interval matrix $[K_k]$ containing all potential optimal gains and hence yielding guaranteed estimation results (without missing some admissible estimations as in the suboptimal case proposed by [2]). In [9], the interval $[K_k]$ of [8] is replaced by a point matrix $K_k$ minimizing the trace of an upper bound of the estimation error covariances, thanks to which the computation time is reduced and the resulted estimators are less conservative. In [1], an optimal upper bound of all symmetric positive semidefinite matrices belonging to a given interval is provided under the form $\alpha^*I$ with $\alpha^* \in \mathbb{R}_+$, thanks to which upper bound expressions are simplified and suitable for advanced optimizations and the computation time is also reduced. Then considering a large class of upper bounds characterized by two real parameters including the one used in [9], [1] also proposes a pointwise optimization for each choice of these scalar parameters.

The present work is a development of [1]. The first motivation drives our researches is to find an uniformly optimized solution of the error estimation covariance upper bounds in terms of their characterized scalar parameters. Furthermore, in the interval approach, a major issue is the conservatism of the resulted estimators due to the one of interval computations accumulated in algorithm iterations. In the worst case, the width of the resulted estimators may explode with a very high value. No study in the above papers addresses the conditions under which the provided algorithms can be controlled to perform with stability, i.e. without explosion in width of the resulted estimators. This is another motivation for our work.

The paper is organized as follows: Section II starts with a brief preliminary part, then introduces the OUBIKF with two stages optimization and guaranteed conditions. In Section III, simulations using the proposed estimation filter applied on an automotive model are provided to emphasize its efficiency. Finally, Section IV is the paper conclusions.

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II. Optimally Bounded Interval Kalman Filter

A. Preliminaries

Denote \( S(n) = \{ M \in \mathbb{R}^{n \times n} : M = M^T \} \) and \( S_+(n) = \{ M \in S(n) : M \succeq 0 \} \), where \( M \succeq 0 \) stands for a real positive semi-definite matrix \( M \). For an \( n \times n \) matrix \( M = (m_{ij}) \), the notations \( \sigma_i(M) \), \( \lambda_i(M) \) \((i = 1, \ldots, n)\) indicate resp. the singular values and eigenvalues of \( M \) among which \( \sigma_{\max}(M) \) and \( \lambda_{\max}(M) \) are the corresponding maximum values. \( \text{tr}(M), \|M\|_1, \|M\|_\text{op} \) are denoted resp. for the trace, operator norm, nuclear norm and Frobenius norm of \( M \).

Let \( M, N \) be two real squared matrices of the same size. Define an order between \( M \) and \( N \) denoted by \( N \preceq M \) if and only if \( M - N \succeq 0 \). \( M \) is called an upper bound of \( N \), and \( N \) a lower bound of \( M \). This partial order is extended to the notion of bounds for a non empty set \( \Omega \) of real squared matrices: \( L \) is an upper (lower) bound of \( \Omega \), denoted by \( \Omega \preceq L \) \((L \preceq \Omega)\), \( \forall M \in \Omega \). If \( P \) and \( Q \) are two upper (lower) bounds of \( \Omega \), then \( P \) is better than \( Q \) if the norm of \( P \) is smaller (greater) than or equal to the norm of \( Q \).

A real interval, denoted by \( [x] \), is a closed connected subset of \( \mathbb{R} \). A real interval matrix \( [X] \) of dimension \( p \times q \) is a matrix with real interval components \( [x_{ij}], i \in \{1, \ldots, p\}, j \in \{1, \ldots, q\} \). Write \( X \in [X] \) to indicate a point matrix \( X = (x_{ij}) \) belonging element-wise to \( [X] \). Define
\[
\sup([X]) = (\sup([x_{ij}])) \quad \text{and} \quad \inf([X]) = (\inf([x_{ij}]))
\]
as element-wise operators and
\[
\text{mid}([X]) = (\sup([X]) + \inf([X]))/2 = (\text{mid}([x_{ij}])),
\]
\[
\text{rad}([X]) = (\sup([X]) - \inf([X]))/2 = (\text{rad}([x_{ij}])),
\]
\[
\text{width}([X]) = \sup([X]) - \inf([X]) = (\text{width}([x_{ij}]))
\]
where the last three matrices are called resp. the midpoint matrix, the radius matrix and the width matrix of \( [X] \). Denote also \( \overline{X} = \sup([X]), \underline{X} = \inf([X]), [X] = [\underline{X}, \overline{X}] \), where \( \overline{X} \) and \( \underline{X} \) will be called resp. the largest and smallest real matrix of \( [X] \) to distinguish with the notion of upper/lower bound matrices defined above. Let \( [X] \) be an \( n \times n \) real interval matrix, denote: \( S([X]) = \{ X \in [X] : X = X^T \} \) \( S_+(([X])) = \{ X \in S([X]) : X \succeq 0 \} \).

The basic interval operators \( \circ \in \{+, -, \times, \div\} \) defined in [10] can be used to compute directly all operations \([u] \circ [v] \) and \( \alpha \circ [u] \), for real intervals \([u], [v] \) and \( \alpha \in \mathbb{R} \), without any further approximation algorithm. Then, interval matrix computations are defined similarly to matrix computations using the basic operators and more general operators are constructed by means of inclusion function [10]. In practice, the package intlab developed for Matlab is used for these computations.

Again, we recall that the conservatism of interval computations is a major issue of all interval filtering and their objective is to find (interval) bounds for real states rather than their point estimators, so it is worthy to define

Definition 1. An interval filter is called C-stable if the widths of interval estimators for all time instant \( k \) are upper bounded by a common constant \( C \).

B. First stages optimization of the Filter

Consider the following linear discrete time dynamical system
\[
\begin{align*}
x_k &= A_k x_{k-1} + B_k u_k + w_k, \quad k \in \mathbb{N}, \\
y_k &= C_k x_k + D_k u_k + v_k,
\end{align*}
\]
in which \( x_k \in \mathbb{R}^{n_x} \) and \( y_k \in \mathbb{R}^{n_y} \) represent state variables and measurements respectively, \( u_k \in \mathbb{R}^{n_u} \) inputs, \( w_k \in \mathbb{R}^{n_w} \) and \( v_k \in \mathbb{R}^{n_v} \) stochastic noises with covariance \( Q_k \) and \( R_k \) respectively.

For any \( K_k \in \mathbb{R}^{n_y \times n_x}, k \geq 1 \), define:
\[
\varphi_k(K_k) \triangleq (I - K_k C_k) P_{k|k-1} (I - K_k C_k)^T + K_k R_k K_k^T,
\]
then \( \varphi_k(K_k) = P_{k|k}, \varphi_k(0) = P_{k|k-1} \), where \( 0 \) is the zero matrix whose dimension is appropriate to the context and will be clarified if necessary under the notation like \( \Omega_{m \times n} \). \( P_{k|k-1} \) and \( P_{k|k} \) are respectively prediction and estimation error covariance in the SKF:
\[
P_{k|k-1} \triangleq \mathbb{E}[(x_k - \hat{x}_{k|k-1})(x_k - \hat{x}_{k|k-1})^T], \ i \in \{0, 1\},
\]
where \( \hat{x}_{k|k-1} \) and \( \hat{x}_{k|k} \) are respectively a priori and a posteriori estimates of the real states \( x_k \).

Let \( S_k = C_k P_{k|k-1} C_k^T + R_k \) and assume that \( S_k \) is nonsingular. Let \( K_k = P_{k|k-1} C_k^T S_k^{-1} \), then
\[
\varphi_k(K_k^*) = (I - K_k^* C_k) P_{k|k} = (I - K_k^* C_k) P_{k|k-1}.
\]

Theorem 1. Consider system (1) with SKF assumptions. Let \( k \geq 1 \). Then:
\[
0 \preceq \varphi_k(K_k^*) \preceq \varphi_k(K_k) \quad \forall K_k \in \mathbb{R}^{n_y \times n_x},
\]
\[
K_k^* = \arg \min_{K_k} \text{tr}(\varphi_k(K_k)) = \arg \min_{K_k} \text{tr}(P_{k|k}).
\]

Proof. Since any covariance matrix is positive semidefinite, then \( \varphi_k(K_k) \geq 0, \forall K_k \), and hence \( \varphi_k(K_k^*) \geq 0 \). By assumptions, \( S_k \in S_+(n_y) \) and is nonsingular, then
\[
0 \preceq (K_k - P_{k|k-1} C_k^T S_k^{-1}) (K_k - P_{k|k-1} C_k^T S_k^{-1})^T
\]
where the right hand side (RHS) of the above expression equals \( \varphi_k(K_k) - \varphi_k(K_k^*) \). Thus, (3) is implied. Then, (4) is concluded using Proposition 2 of [1].

Assumptions A1: Matrices \( A_k, B_k, C_k, D_k \) are unknown and belonging to given interval matrices \( [A], [B], [C], [D] \) respectively. \( u_k, v_k \) are centered Gaussian vectors with covariance matrices \( Q_k \) and \( R_k \) belonging respectively to given interval matrices \( [Q] \) and \( [R] \). The initial state \( x_0 \) is also Gaussian with mean \( \mu_0 \) and covariance matrix \( P_0 \). In addition, \( x_0, \{ v_1, \ldots, v_n \} \) and \( \{ v_1, \ldots, v_n \} \) are mutually independent.

Aim: The aim of the Filter is to get estimate intervals \( [\hat{x}_{k|k}] \) which contain all admissible estimates \( \tilde{x}_{k|k} \) of states \( x_k \) induced by mixed uncertainties. Then related confidence intervals are yielded according to the 3-\sigma rule since \( x_k \)'s follow the multivariate normal distribution.

Principle: OUBIKF follows the same structure of the SKF. In the prediction step, thanks to interval computations, the a priori estimate \( [\hat{x}_{k|k-1}] = [A][\hat{x}_{k-1|k-1}] + [B]u_k \) is provided. It contains all admissible estimates \( \tilde{x}_{k|k-1} = A_k \tilde{x}_{k-1|k-1} + B_k u_k \) for all values of \( A_k \in [A], B_k \in [B] \). \( \tilde{x}_{k|k-1} \) and \( \hat{x}_{k|k-1} \) is in the correction step, an interval estimator \( [\hat{y}_{k}] \) is provided, in which \( \hat{y}_{k} = [C][\hat{x}_{k|k-1}] + [D]u_k \) and the gain \( K_k \) is a point matrix chosen in an optimal way. The gain \( K_k \) is chosen by a two stages optimization considering the class of

\footnote{The nonsingularity of \( S_k \) can be assured if \( R_k \) is assumed to be positive definite or more strictly measurement noises are assumed to be vectors of independent random components. In practice, the pseudo-inverse \( S_k^+ \) is used instead with notice that \( S_k^+ = S_k^{-1} \) when \( S_k \) exists.}
upper bounds $\Gamma \triangleq \{\mathbb{F}_S(K, \beta) : S = (P_{[k:k]}) \leq \mathbb{F}_S(K, \beta)\}$, where $[P_{[k:k]}]$ is the interval matrix containing all admissible estimation error covariances $P_{[k:k]}$ and the form of $\mathbb{F}_S(K, \beta)$ will be clarified in Theorem 2c. $\Gamma$ also includes the upper bound of $S_k([P_{[k:k]}])$ used in [9]. Each upper bound in $\Gamma$ is seen as a function of two arguments: gain matrix $K_k$ and real parameter $\beta > 0$. The optimization is performed in two stages, first in terms of $K_k$ and then with respect to $\beta$ in order to get the optimal bound $\mathbb{F}_S^*(K, \beta)$ of $S_k([P_{[k:k]}])$ among others in $\Gamma$. Then, the Filter is developed and applied with the guaranteed conditions under which the model should be designed to obtain the Filter stability (Definition 1) thanks to the fact that the $\text{tr} \{\mathbb{F}_S^*\}$ is non-asymptotically and asymptotically bounded.

**Theorem 2.** Consider system (1) with assumptions A1. Let $M = \text{mid}(C)$, $R_{ij}$ be a matrix whose elements are zero except its $ij$-th element equals to $\text{rad}(C)$, $\mathbb{F}_S$ the non null radius of $\text{rad}(C)$ and $\Sigma = \sum_{i,j} R_{ij}^T \Sigma R_{ij}$.

The RHS of (5) is upper bounded by the RHS of (6) and $\sum_{i,j} R_{ij}^T \Sigma R_{ij}$ can be used to get the optimal bound $\mathbb{F}_S^*$ of $S_k([P_{[k:k]}])$. The following statements hold:

1. If $K_{[k:k]} = \{K_{[k:k]}\}$, then $K_{[k:k]} \in \mathbb{F}_S([K_{[k:k]}])$.
2. $\mathbb{F}_S([K_{[k:k]}]) \leq \mathbb{F}_S([K_{[k:k]}])$.
3. $\mathbb{F}_S([K_{[k:k]}]) \in \mathbb{F}_S([K_{[k:k]}])$.

Then, (5) holds noting that $\inf_{\beta > 0} \mathbb{F}_S(K, \beta) > 0$.

**Remark 1.** In [9], the choice $\beta = \sigma_{i,j,u,v} = 1$ is used. In [1], the choice $\beta = \beta > 0$, the choice $\sigma_{i,j,u,v} = \sigma = 0$, $\forall i,j,u,v$, $\eta_{i,j,u,v}$ is used regardless the condition $\sigma_{i,j,u,v} = \sigma = 1$. In the present work, a circumspect study of the minimization of $\text{tr} \{\mathbb{F}_S(K, \beta)\}$ is provided, noting that $\inf_{\beta > 0} \mathbb{F}_S(K, \beta) > 0$, is considered to find its minimum $\Phi_k \triangleq \inf_{\beta > 0} \mathbb{F}_S(K, \beta)$.

The following notations are used:

1. All notations defined in Theorems 1 and 2.
2. $\varphi_k, K_k, S_k, R_k$, $\Sigma_k, \eta$, $\sigma_k, \gamma_k, \mathbb{F}_S(K_k, \beta)$, $\Phi_k, \mathbb{F}_S^*(K, \beta)$.
3. $r = \text{rank}(M)$, $\{A_i\}_{i=1,...,r}$ are non null eigenvalues of $\text{MM}^T$, $\text{dmin} = \min \{\Sigma_i \neq 0, i = 1,...,n_y\}$, $\text{dmax} = \max \{\Sigma_i \neq 0, i = 1,...,n_y\}$.

**Lemma 1.** Let $\alpha > 0$, $\beta > 0$, $\alpha(\beta) = \alpha(1 + \beta_0, \beta)$. Then

$$\lim_{\beta \to \infty} \xi(\beta) = \alpha_\infty x_{\infty} \text{tr}(\text{MM}^T + \beta_c I_{n_y})^{-1} M.$$ 

Furthermore:

1. If $\eta_{x_{\infty}} = 1, r_1, \beta_{1,2} > 0$, then $\xi(\beta)$ is non-decreasing and

$$\lim_{\beta \to \infty} \xi(\beta) = \lim_{\beta \to \infty} \xi(\beta), \quad \sup_{\beta > 0} \xi(\beta) = \lim_{\beta \to \infty} \xi(\beta).$$

2. If $\eta_{x_{\infty}} > 1, r_1, \beta_{1,2} > 0$, then $\xi(\beta)$ is non-decreasing and

$$\lim_{\beta \to \infty} \xi(\beta) = \lim_{\beta \to \infty} \xi(\beta), \quad \sup_{\beta > 0} \xi(\beta) = \lim_{\beta \to \infty} \xi(\beta).$$

**Proposition 1.** Let $k \geq 1, \epsilon > 0$, $c_1, c_2 = \text{dmin} + \frac{\gamma}{\alpha_{(x_{\infty})} + \alpha_{(x_{\infty})}}$. Let $h(\beta) = \alpha_k(1 + \beta_0 / \beta) [n_x + r]$, $\beta = \alpha_k(1 + n_0 / \beta) n_x$, and for $i \in \{1, 2\}$,

$$\xi_{i,k}(\beta) = \alpha_k(1 + n_0 / \beta) \eta_{x_{\infty}} \text{tr}(\text{MM}^T + \beta c_i K_{[k:k]}(I_{n_y} - M_{[k:k]}))^{-1} M).$$

Then for all $\beta < \xi$:

$$0 \leq h(\beta) \leq \xi_{1,k}(\beta) \leq \phi_k(\beta) \leq \xi_{2,k}(\beta) \leq g(\beta).$$

Furthermore:

1. If $n_x = r$ and $\lambda_i = \gamma_{n_0} / \gamma_{(x_{\infty})}$, then $\lim_{\beta \to \infty} \phi_k(\beta) = g(\beta)$

**Remark 2.** Figure 1 illustrates Proposition 1 in which (10) is highlighted. Lemma 1 is technically needed for Proposition 1,
while the last one provides the bounds of $\phi_k(\beta)$ together with its infimum value $\Phi_k^*$ in two accessible cases.

Figure 1: Left: $h_k(\beta)$ and $g_k(\beta)$ at a fixed time $k \geq 1$. Right: An example of $\phi_k(\beta)$ for the case $n_x = r$ and $\lambda_i \geq n_0 d_{max} + \gamma/\alpha_k$, $\forall i = 1, ..., r$ at a fixed time $k \geq 1$.

**Guaranteed conditions:** It is difficult to get the exact infimum of $\phi_k(\beta)$, noted $\Phi_k^*$, but its bounds and limits can be determined conditioning:

$$C_1: \begin{cases} n_x = r \\ \lambda_i \geq n_0 d_{max} + \gamma/\alpha_k, \quad \forall i = 1, ..., r. \end{cases}$$

Using Proposition 1 under conditions $C_1$, the following expression can be obtained:

$$0 \leq \lim_{\beta \to 0} \phi_k(\beta) - \Phi_k^* \leq \alpha_k n_0 (d_{max} - d_{min}) tr\{(M M^T)^+\},$$

in which $d_{max}, d_{min}$ are controllable. So, the minimization of $\phi_k(\beta)$ (exactly or approximately) consists in how to design the system under consideration to reach conditions $C_1$ and control $d_{max}, d_{min}$ in an appropriate way.

**Design of conditions $C_1$:**

**Condition 1:** $n_x = r$. Since $M \in \mathbb{R}^{n_y \times n_x}$, $r \leq \min\{n_x, n_y\}$, to get $r = n_x$, it requires:

- $n_y \geq n_x$.
- $M$ has $n_x$ linearly independent columns.

Note that the number of output measurements $n_y$ is not necessary the number of physical sensors $n_x$. In view of the system design, it is not prohibited (and it is possible) to design more measurement outputs than the number of states, although the number of sensors can be not sufficient. The missing measurements due to the lack of sensor can be (not always) estimated by several ways, e.g., by an observer considered as a virtual sensor or by known constraint conditions on the bounds of these measurements. This situation also leads to the rationality of using the interval matrix $[C]$ to model the bounded measurement uncertainty.

The second requirement can be regularized numerically in particular for the interval context. A regularization $[C] \leftarrow [C] + \varepsilon I$ with appropriate small (point matrices) $\varepsilon \in \mathbb{T}$ can be used, if it is necessary, so that the (new) matrix $[C]$ still verified all constraint conditions of the system and $M = \text{mid}([C])$ has $n_x$ linearly independent columns.

**Condition 2:** $\lambda_i \geq n_0 d_{max} + \gamma/\alpha_k$, $\forall i = 1, ..., r$.

This condition is equivalent to $\lambda_{\min} \geq n_0 d_{max} + \gamma/\alpha_k$, where $\lambda_{\min} = \min_1 \ldots r (\lambda_i)$. This condition is achievable thanks to the Lemma 2 below.

**Lemma 2.** Let $\delta = \max_{i,j} \{\text{rad}([c_{ij}])\}$ with $[C] = ([c_{ij}])$. If for some $s \in (0, 1)$, the following two expressions hold

- $0 \leq \delta \leq \sqrt{s \frac{\lambda_{\min}}{n_0 \gamma}}$
- $\alpha_k \geq \max \{1 - \gamma \lambda_{\min}, \sup P \in S_+(r_{n_{x}(k-1)}) \{\lambda_{\max}(P)\}\}

then the condition $\lambda_{\min} \geq n_0 d_{max} + \gamma/\alpha_k$ is verified.

**Proof.** By assumptions, $d_{max} \leq (s \lambda_{\min}/n_0)$ and $1/\alpha_k \leq (1 - s)\lambda_{\min}/\gamma$, implying that $n_0 d_{max} + \frac{\gamma}{\alpha_k} \leq \lambda_{\min}$. □

The following lemma is used for Theorem 3 computations. Only its third statement needs the first condition of $C_1$.

**Lemma 3.** The following statements hold:

a) $K^\top \preceq M^T (M M^T)^+ M^T \in \mathbb{R}^{n_x \times n_y}$.

b) $\lim_{\beta \to 0} K_{k, \beta} = K^\top$ and $\lim_{\beta \to 0} \varphi_{k}(K_{k, \beta}) = \varphi_k(K^\top)$.

c) If $\text{rank}(M) = n_x$ then $I_{n_x} \rightarrow K^\top = M = 0_{n_x \times n_y}$.

**Remark 3.** Assume that $\text{rank}(M) = n_x$ and assumptions of Lemma 2 are verified. Then

$$\varphi_{k}(K^\top) \leq \varphi_{k}(K_{k, \beta}) \leq \varphi_{k}(K^\top) \leq \alpha_k n_0 d_{max} + \gamma/\alpha_k \leq \alpha_k I_{n_x},$$

where $P_{k,k} = \varphi_{k}(K^\top)$ is the error covariance matrix associated with the use of $K_{k} = K^\top$.

Assume further that $S_+(0) \leq \lambda_1 I_{n_x}$, $S_+(A[A]^T) \leq \lambda_2 I_{n_x}$, $S_+(P_0) \leq \lambda_3 I_{n_x}$, and $\lambda_{\min}/\lambda_{\max} \leq L < 1$. Let $\Psi_L = \lambda_1 n_0 \nu_0 \gamma^2/\lambda_{\min}(1-L)$ and $\Psi_L(k) = \Psi_L + (\tau_0 - \Psi_L) L^k$, then

$$P_{k,k} \leq \psi_{k}(L(k)) I_{n_x}, \quad M S E(K^\top) \leq \text{tr}\{P_{k,k}\} \leq \psi_{k}(L(k)) n_x, \quad \text{(12)}$$

$$P_{k+1,k} \leq (2 \Psi_L(k) + \lambda_1) I_{n_x}. \quad \text{(13)}$$

**Proof.** From Theorems 1-2, one gets:

$$0 \leq \varphi_{k}(K^\top) \leq \lim_{\beta \to 0} \varphi_{k}(K_{k, \beta}) \leq \varphi_{k}(K^\top) \leq \lim_{\beta \to 0} \varphi_{k}(K_{k, \beta}) \leq \varphi_{k}(K^\top);$$

By assumptions of the theorem, the conditions $C_1$ holds, then

$$\lim_{\beta \to 0} \varphi_{k}(K^\top) \leq \lambda_k \leq \lambda_{\min} - \delta^2 n_x \gamma/\lambda_{\min},$$

in which $\lambda_k \leq \lambda_{\min} - \delta^2 n_x \gamma/\lambda_{\min}$ and hence

$$\lim_{\beta \to 0} \varphi_{k}(K^\top) \leq \lambda_k \leq \alpha_k n_0 \gamma^2 n_x + \gamma/\alpha_k \leq \lambda_{\min}.$$
where the last inequality holds thanks to $\lambda_{\text{min}} \geq n_0 \delta^2 n_x + \frac{\gamma}{\alpha_k}$.

By recursion, we get

$$P_{k | k} = (A_{k,1}^\circ P_{0 | 0} (A_{k,1}^\circ)^T + \sum_{i=1}^{k-1} (A_{k,i+1}^\circ \dot{C}_i) Q_i (A_{k,i+1}^\circ \dot{C}_i)^T + \sum_{i=1}^{k-1} (A_{k,i+1}^\circ \dot{K}) R_i (A_{k,i+1}^\circ \dot{K})^T),$$

where $A_{k,i}^\circ = A_k A_{k-1} \ldots A_{k+i+1} A_k$ if $s \leq k$ and $A_{k,s}^\circ = I$ if $s > k$. $C_k = I - \dot{K}^\circ C_k$, $\dot{A}_k = \dot{C}_k A_k$.

For any $p \geq 1$, $C_p \in [C]$ is decomposed as $C_p = M + \Delta_p$, $\Delta_p = \sum_{i \in \Omega(p)} R_i I_{ij}$, $\Omega(p) \in [-1,1]$ and hence, using Lemma 3 and (15), we get

$$\left(I - \dot{K}^\circ C_p\right) \left(I - \dot{K}^\circ C_p^T\right) = \dot{K}^\circ \Delta_p \dot{K}^\circ \dot{K}^\circ \geq \dot{K}^\circ \left(n_0 \Sigma \right) \dot{K}^\circ \leq n_0 \delta^2 n_x \dot{K}^\circ \dot{K}^\circ \leq n_0 \delta^2 n_x \frac{1}{\lambda_{\text{min}}} I_{n_x},$$

implying that $\dot{A}_p \dot{A}_p^\circ \leq n_0 \delta^2 \frac{n_x}{\lambda_{\text{min}}} I_{n_x}$.

Substituting these results into $P_{k | k}$'s expression above, then

$$P_{k | k} \preceq \sigma_0 \ell_i \ell_i \ell_i + \frac{\lambda_{\text{min}} n_0 n_x \delta^2}{\lambda_{\text{min}}} \sum_{i=1}^{k-1} \ell_i \ell_i \ell_i$$

and the conclusion holds noting that $\ell_i = \frac{\lambda_{\text{min}} n_0 n_x \delta^2}{\lambda_{\text{min}}} \leq L < 1$ and $\sum_{i=1}^{k-1} \ell_i = \frac{1 - \ell_i}{1 - \ell_i}$.

Algorithm 1 OUBIKF ALGORITHM

**Initialization:** $\bar{x}_{0 | 0}, P_{0 | 0}, [A], [B], [C], [D], [Q], [R], s, \lambda_{\text{min}}, u_k, y_k, k = 1, 2, 3, ..., N$

Find $n_0$ and find $\gamma$ such that $S_k([R]) \leq \gamma I$

$\bar{K} = \text{midx}([C]) \ast \text{radC} = \text{rad}([C]) \ast \Sigma = \text{diag} \{\text{radC} \ast \text{radC} \}$.

for $k = 1, 2, 3, ..., N$ do

**Prediction step:**

$\bar{x}_{k | k-1} = [A] \bar{x}_{k-1 | k-1} + [B] u_k$

$P_{k | k-1} = [A] P_{k-1 | k-1} [A]^T + [Q]$

Find $\alpha_k$ such that $S_k([P_{k | k-1}]) \preceq \alpha_k I$

$\alpha_k = \max \{\gamma / \lambda_{\text{min}}, 1\}.$

**Correction step:**

$\bar{x}_{k | k} = \bar{K} \left(-1, \ldots, 1\right) \ast \text{radC} \left[\bar{x}_{k-1 | k-1}\right] + \bar{K}^\ast [y_k - [D] u_k]$

$P_{k | k} = \bar{K} \left[\alpha_k n_0 \Sigma + \gamma \ell_i I_{n_x}\right] \bar{K}^\ast$

end for

Remark 4. Confidence intervals are defined by

$$C_{k} = \left[\inf_{[\bar{x}_{k | k}]} [\bar{x}_{k | k}] - h \sqrt{P_{k | k}}, \sup_{[\bar{x}_{k | k}]} [\bar{x}_{k | k}] + h \sqrt{P_{k | k}}\right],$$

for $k = 1, \ldots, n_x$ and $h = 1, 2, 3$, which contain the states $x_k$ with probabilities at least 68%, 95%, 99.7% according to $h$.

III. SIMULATION

In this section, the OUBIKF Algorithm is applied to a model taken from automotive domain presented in [11]. This model is a nonlinear continuous-time model which has been discretized/linearized and thus given under the form (1). A discretization is applied with a sampling time $T = 0.05s$ to get matrices $A_d, B_d, C_d, D_d$ (non interval and independent of time instant $k$) according to equations in (1). Then, interval matrices $[A], [B], [D]$ are generated as follow: for $F \in \{A_d, B_d, D_d\}$, let $F = \text{mid}([F])$ and choose the radii $\text{rad}([F])$ at random in $[0, 0.5]$, $[Q]$ and $[R]$ are generated in the same way, their diagonal elements being intervals of positive real numbers.

Choose $M = \text{mid}([C]) = C_d$. With this choice, rank($M$) = $n_x$, so the first part of conditions C1 is satisfied. The second part of conditions C1 is reached using Remark 3 to compute $L, s, \delta$ with the choices $\Psi = 10 \gamma / \lambda_{\text{min}}$ and $n_0 = n_x n_y$.

Then $[C]$ is generated in the same way of $[A]$ so that $\max_{ij} \{\text{rad}([c_{ij}])\} \leq \delta$.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
$\Psi_L$ & $\lambda_{\text{min}}$ & $\lambda_1$ & $\lambda_2$ & $\gamma$ & $s$ & $L$ & $\delta$ \\
\hline
3.84 & 3.49 & 0.91 & 2.30 & 1.34 & 0.24 & 0.82 & 0.23 \\
\hline
\end{tabular}
\caption{Parameter computation results.}
\end{table}

Table I: Parameter computation results.

Inputs $u_k$ are simulated according to a dynamic change for $N = 864$ iterations. The initial state is chosen at $x_0 = (0,0)^T$. At each step $k$, chose $A_k, B_k, C_k, D_k, Q_k, R_k$ in corresponding interval matrices and so that $Q_k$ and $R_k$ are positive semi-definite. Then $w_k, v_k$ are simulated and $\{x_k, y_k\}_{k \in \mathbb{N}}$ are computed according to system (1). The Algorithm is initialized at $[x_0] = ([0.5, 0.5], [-0.5, 0.5])^T$ and $P_{0 | 0} = \text{max}\{\text{diag}([Q])\} I$.

The 95% confidence intervals $C_{k | k}$ contain all real states $x_k$ as shown in Figure 2. The computation time using the OUBIKF with the new setting of the present work is improved against the OUBIKF with the setting proposed in [1] (Table II), while the last one has been shown by simulation to be more efficient in computation time against its precursor [9].

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
OUBIKF & With new settings & With settings of [1] \\
\hline
Computation time (s) & 3.33 & 3.02 \\
\hline
\end{tabular}
\caption{OUBIKF with two settings.}
\end{table}

Figure 2: Estimation results. For $i = 1, 2$, the center green line: real states $x_{k,i}^i$, the blue lines: 95% confidence intervals $C_{k,i}^i$.

IV. CONCLUSION

The OUBIKF Algorithm proposed in [1] is enhanced theoretically and practically by the two stages optimization and the guaranteed conditions C1.

Under these conditions, the optimal upper bound is reached approximately by the chosen $P_{k | k}$ whose trace is closely closed to the optimal value $\Phi_k^*$. Also, the considered Algorithm is ensured to perform with stability in the sense that the trace of $P_{k | k}$ is non-asymptotically and asymptotically bounded and can be controlled, implying that there is no width explosion of the yielded estimators. In addition, the trace of $P_{k | k}$ is smaller than the one of the upper bound $\alpha_k \ell_i I_{n_x}$ of $S_{+}(\{P_{k | k-1}\})$ in the prediction step.

Thanks to deep analysis in limit results, expressions of the correction step are simplified and many factors of them can be computed off-line. It reduces the algorithm computation time in comparison Algorithm 1 with others used in [2], [8], [9].
By (10), we get for all \( \epsilon > 0 \):

\[
0 \leq \alpha_k(n_x - r) \leq \inf_{\beta > 0} \xi_{1,k}(\beta) \leq \alpha_k n_x,
\]

\( \circ \) \( 0 \leq \lim_{\beta \to 0} \xi_{1,k}(\beta) \leq \lim_{\beta \to 0} \phi_k(\beta) \leq \lim_{\beta \to 0} \xi_{2,k}(\beta) \),

and, beside, \( \Phi_k^* \leq \lim_{\beta \to 0} \phi_k(\beta) \). Then using Lemma 1, the two statements a) and b) of the proposition are concluded. □

Proof of Lemma 3. a) The first expression is verified thanks to Proposition 3.2 of [12].

b) Since \( A^+ = A^{-1} \) when the later exists and applying the Tikhonov’s regularization from Theorem 4.3 of [12], we get

\[
\lim_{\beta \to 0} K_{\epsilon_k, \beta} = \lim_{\beta \to 0} M^T \left( M M^T + \beta \Sigma + \frac{\gamma^2}{\alpha_k(\beta + \eta \alpha)} I \right)^{-1} = \lim_{\beta \to 0} M^T \left( M M^T + \beta \Sigma + \frac{\gamma^2}{\alpha_k(\beta + \eta \alpha)} I \right)^{-1} 
\times \left( \left( M M^T + \beta \Sigma + \frac{\gamma^2}{\alpha_k(\beta + \eta \alpha)} I \right)^{-1} \right)^{-1} 
= \lim_{\eta \to 0} M^T \left( M M^T \right)^2 + \eta^2 I^{-1} 
= M^T (M M^T)^+ = K^* 
\]

\( \lim_{\beta \to 0} \phi_k(K_{\epsilon_k, \beta}) = \phi_k(K^*) \) thanks to \( \lim_{\beta \to 0} K_{\epsilon_k, \beta} = K^* \) and \( \phi_k(K^*) = 0 \).

By definition of Moore-Penrose pseudoinverse, we get \( M^+ M = M \) and hence \( M(I_{n_x} - M^+ M) = 0_{n_x \times n_x} \).

Let \( X = I_{n_x} - M^+ M \). By assumption \( \text{rank}(M) = n_x \), the null space of \( M \) is \( \{0_{n_x \times 1}\} \). It follows that all columns of \( X \) equal \( 0_{n_x \times 1} \) and hence \( X = I_{n_x} - K M = 0_{n_x \times n_x} \). □

References


