ICIC Express Letters
Part B: Applications
Volume **10**, Number **1**, January **2019**

ICIC International ©2019 ISSN 2185-2766
pp. **81–88**

NOVEL APPROACH TO ROBUST CONTROLLER DESIGN FOR CONTINUOUS-TIME SYSTEMS

Vojtech Veselý and Martin Ernek

Faculty of Electrical Engineering and Information Technology
Slovak University of Technology in Bratislava
Ilkovicova 3 81219 Bratislava, Slovak Republic
vojtech.vesely@stuba.sk

Received June 2018; accepted September 2018

Abstract. *This paper is devoted to obtaining the novel robust controller design procedure for uncertain polytopic linear continuous time systems. The proposed method is based on the Bellman-Lyapunov equation for the suboptimal structure case. The obtained robust controller with output/state feedback ensures in the frame of H_2 guaranteed cost and parameter dependent quadratic stability. The performance and quality are given as augmented quadratic cost function known as QSR (states, states derivatives and input). Novel approach ensures that designed PID controller gains belong to the obtained interval. The proportional and integral controller gains may change simultaneously or independently. The obtained controller gains intervals should be used by the controller designer, e.g., to increase the control quality, and ensure the plant input/output constraints. The robust stability of the closed loop system and performance does not violate when the gains change within the obtained intervals and the rates of the controller gains changes are not over the given value. In the example we ensure that maximal value of controller parameters rates is given as* $\max(\dot{\theta}) = 0.5/sec$. *The above possibilities open the new way to increase design quality and performance. Numerical example is given to illustrate the properties and effectiveness of the proposed method.*
Keywords: Robust controller, Linear continuous time system, Parameter-dependent Lyapunov function, Bellman-Lyapunov equation

1. **Introduction.** Robust control is frequently encountered in various physical, industrial and engineering real life systems as plant robust controller, robust controller of hybrid systems, robust predictive controller, robust gain scheduled controller, etc. The application survey of robust controller theory may reader consult in [1, 2]. Since robust control increases the stability and performance of the closed loop system, it has received much attention during the past decades. Numbers of authors dedicate their work to robust controller design, e.g., [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. In this paper we pursue the idea in [3, 17] which introduces new auxiliary matrices to the robust controller design procedure, which may decrease the conservativeness of controller design [18, 19]. The aim of the present work is twofold. Firstly novel robust stability conditions with less conservativeness in the frame of H_2 will be derived. Secondly, the robust controller designer will obtain more information about the controller parameters, specifically one obtaining the controller parameters intervals within the parameters may change without violation of the closed loop system robust stability and performance. The designer may use above properties within the dynamic process to change the controller parameters for making the better performance of the closed loop system.

The notations applied in the paper are standard in the field of robust controller design. Our notations are standard. $P \in R^{m\times n}$ denotes the set of real $m \times n$ matrices, I_m is an $m \times m$ identity matrix, $P > 0$ ($P \geq 0$) is real symmetric, positive definite (semidefinite)

DOI: 10.24507/icicelb.10.01.81

matrix. Matrices, if not explicitly stated, are assumed to have compatible dimensions. This paper is organized as follows. Section 2 gives preliminaries and problem formulation. Section 3 gives our main results in the form of Bilinear Matrix Inequalities (BMI) and convex robust stability conditions with respect to uncertainties. Section 4 shows the example and Section 5 gives conclusion.

2. **Problem Statement and Preliminaries.** We consider the following linear uncertain continuous time systems

$$\dot{x} = A(\xi)x + B(\xi)u, \quad y = Cx \tag{1}$$

where $x \in R^n$ is the plant state, $u \in R^m$ is control input, and $y \in R^l$ is the plant controlled output; matrices $A(\xi)$, $B(\xi)$ belong to the convex set of a polytope with "N" vertices

$$\Omega := \left\{ A(\xi) \in R^{n\times n}, B(\xi) \in R^{n\times m} : A(\xi), B(\xi) = \sum_{i=1}^{N} (A_i, B_i)\xi_i, \right. \\ \left. \sum_{i=1}^{N} \xi_i = 1, \xi \geq 0, \dot{\xi}_i \in \left\langle \underline{\dot{\xi}_i}, \overline{\dot{\xi}_i} \right\rangle \right\} \tag{2}$$

A_i, B_i, C are constant matrices of corresponding dimensions; ξ_i, $i = 1, 2, \ldots, N$ are constant or time varying but unknown parameters. It is supposed that system matrices $(A(\xi), B(\xi), C)$ allow design of the PID controller. For more details see [10]. To assess performance quality in the frame of H_2 an augmented quadratic cost function is proposed:

$$J_c = \int_0^\infty J\left(x, \dot{x}, u\right) dt \tag{3}$$

where

$$J\left(x, \dot{x}, u\right) = x^T Q x + \dot{x}^T S \dot{x} + u^T R u$$

where $Q, S \in R^{n\times n}$ are positive definite (semidefinite) matrices, and $R \in R^{m\times m}$ is positive definite matrix. Equality (3) should be rewritten as follows

$$J(.) = \begin{bmatrix} \dot{x}^T & x^T & u^T \end{bmatrix} \begin{bmatrix} S & 0 & 0 \\ 0 & Q & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} \dot{x} \\ x \\ u \end{bmatrix} \tag{4}$$

In this paper the design of robust PID controller with static output feedback problem is studied.

Problem 2.1. *Design a robust PID controller with static output feedback and control algorithm:*

1.

$$u = K_p(\theta)C_p x + K_i(\theta)C_i x + K_d C_d \dot{x} \tag{5}$$

2.

$$u = K_p(\theta)C_p x + K_i(\vartheta)C_i x + K_d C_d \dot{x} \tag{6}$$

where $K_p(\theta)$, $K_i(\vartheta)$, K_d are proportional, integral and derivative gain matrix of the PID controller with corresponding dimensions.

$$K_j(\theta) = K_{j0} + K_{j1}\theta, \quad j = p, i \\ K_i(\vartheta) = K_{i0} + K_{i1}\vartheta \tag{7}$$

We assume that both lower and upper bounds of auxiliary parameters θ, ϑ and their rates are known. Specifically:

$$\theta \in \left\langle \underline{\theta}, \overline{\theta} \right\rangle, \quad \vartheta \in \left\langle \underline{\vartheta}, \overline{\vartheta} \right\rangle \tag{8}$$

$$\dot{\theta} \in \left\langle \underline{\dot{\theta}}, \overline{\dot{\theta}} \right\rangle, \quad \dot{\vartheta} \in \left\langle \underline{\dot{\vartheta}}, \overline{\dot{\vartheta}} \right\rangle \tag{9}$$

The aim of introducing θ, ϑ is that during the controller design procedure are obtained matrices K_{ji}, $j = p, i$ and in this way the designer obtains the intervals where the controller parameters may change. In the above controller parameter intervals robust stability and performance are guaranteed. Other function of θ, ϑ and obtained intervals may be used to increase damping of the closed loop system. The controller parameters should change with the function of any plant or exogenous variables. To guarantee the robust stability and performance in the frame of H_2 the Bellman-Lyapunov equation will be used [20].

Theorem 2.1. *Consider the uncertain system (1). Control Algorithm (5) or (6) is the guaranteed cost control law for the closed loop system if and only if there exists Lyapunov function $V(x,\theta,\xi)$ such that the following condition holds:*

$$B_e(x,u,\xi,\theta) = \frac{dV(.)}{dt} + J(x,\dot{x},u) = -\varepsilon x^T x,\ \varepsilon \geq 0,\ \varepsilon \to 0 \tag{10}$$

Equation (10) is known as Bellman-Lyapunov equation. Function V(.) which satisfies (10) is the Lyapunov function. Note that for concrete structure of the Lyapunov function the obtained design procedure may reduce from "if and only if" to "if".

3. **Robust Controller Design.**

Case 3.1. *Controller parameters $K_p(\theta)$, $K_i(\theta)$ change simultaneously.*
In this case we assume that P and I part controller parameters change together with θ. Assume, Lyapunov function in (10) is given in the following particular structure:

$$V(x,\theta,\xi) = x^T P(\theta,\xi)x = x^T(P_0(\xi) + P_1(\xi)\theta)x \tag{11}$$

and

$$P_j(\xi) = \sum_{i=1}^{N} P_{ji}\xi_i,\ j = 0,1;\ i = 1,2,\dots,N$$

Time derivative of Lyapunov function (11):

$$\frac{dV(.)}{dt} = \left[\begin{array}{ccc} \dot{x}^T & x^T & u^T \end{array}\right] \left[\begin{array}{ccc} 0 & P(\theta,\xi) & 0 \\ P(\theta,\xi) & P\left(\dot{\theta},\dot{\xi}\right) & 0 \\ 0 & 0 & 0 \end{array}\right] \left[\begin{array}{c} \dot{x} \\ x \\ u \end{array}\right] \tag{12}$$

where

$$P\left(\dot{\theta},\dot{\xi}\right) = \sum_{i=1}^{N}\left(\sum_{k=1}^{N} P_{0k}\dot{\xi}_k + \sum_{k=1}^{N} P_{1k}\dot{\xi}_k\theta + \sum_{k=1}^{N} P_{1k}\dot{\theta}\right)\xi_i$$

We introduce six auxiliary matrices with dimensions $N_1, N_2 \in R^{n\times n}$; $N_3 \in R^{n\times m}$, $N_4, N_5 \in R^{m\times n}$; $N_6 \in R^{m\times m}$ to separate system matrices from Lyapunov function:

- $$2\left(N_1\dot{x} + N_2 x + N_3 u\right)^T\left(\dot{x} - A(\xi)x - B(\xi)u\right) = 0$$
- $$2\left(N_4\dot{x} + N_5 x + N_6 u\right)^T\left(-K_d C_d\dot{x} - \left(K_p(\theta)C_p + K_i(\theta)C_i\right)x + u\right) = 0 \tag{13}$$

Denote $K_c(\theta) = K_p(\theta)C_p + K_i(\theta)C_i$. Summarizing performance (4), time derivative of Lyapunov function (12), and (13) one obtains Bellman-Lyapunov equation in the form:

$$B_e(.) = v^T W v \leq 0;\ v^T = \left[\begin{array}{ccc} \dot{x}^T & x^T & u^T \end{array}\right] \tag{14}$$
$$W = \{w_{ij}(\xi)\}_{3\times 3}$$

and

$$w_{11}(\xi) = S - N_4 K_d C_d - C_d^T K_d^T N_4 + N_1^T + N_1$$
$$w_{12}(\xi) = P(\theta,\xi) - N_4^T K_c(\theta) - C_d^T K_d^T N_5 - N_1^T A(\xi) + N_2$$

$$w_{13}(\xi) = N_4^T - C_d^T K_d^T N_6 - N_1^T B(\xi) + N_3$$
$$w_{22}(\xi) = -N_2^T A(\xi) - A(\xi)^T N_2 - N_5^T K_c(\theta) - K_c(\theta)^T N_5 + Q + P\left(\dot{\theta}, \dot{\xi}\right)$$
$$w_{23}(\xi) = N_5^T - K_c(\theta) N_6 - N_2^T B(\xi) - A(\xi)^T N_3$$
$$w_{33}(\xi) = R - N_3^T B(\xi) - B(\xi)^T N_3 + N_6^T + N_6$$

Due to that matrix W is convex with respect to θ and ξ one can split matrix W as follows: $W = \sum_{i=1}^{N} W_i \xi_i \leq 0$ and

$$W_i = W_{0i} + W_{1i}\theta \leq 0; \quad i = 1, 2, \dots, N \tag{15}$$

where $W_{0i} = \{w_{0kl}(i)\}_{3\times 3}$; $W_{1i} = \{w_{1kl}(i)\}_{3\times 3}$, $i = 1, 2, \dots, N$

$$w_{011}(i) = S - N_4^T K_d C_d - C_d^T K_d^T N_4 + N_1^T + N_1$$
$$w_{111}(i) = 0$$
$$w_{012}(i) = P_{0i} - N_4^T K_{0c} - C_d^T K_d^T N_5 - N_1^T A_i + N_2$$
$$w_{112}(i) = P_{1i} - N_4^T K_{1c}$$
$$w_{013}(i) = N_4^T - C_d^T K_d^T N_6 - N_1^T B_i + N_3$$
$$w_{113}(i) = 0$$
$$w_{022}(i) = -N_2^T A_i - A_i^T N_2 - N_5^T K_{c0} - K_{c0}^T N_5 + Q + P\left(\dot{\theta}, \dot{\xi}\right)_0$$
$$w_{122}(i) = -N_5^T K_{c1} - K_{c1}^T N_5 + P\left(\dot{\theta}, \dot{\xi}\right)_1$$
$$w_{023}(i) = N_5^T - K_{c0}^T N_6 - N_2^T B_i - A_i^T N_3$$
$$w_{123}(i) = -K_{c1}^T N_6$$
$$w_{033}(i) = R - N_3^T B_i - B_i^T N_3 + N_6^T + N_6$$
$$w_{133}(i) = 0$$

Obtained results are summarized in the following theorem.

Theorem 3.1. *Uncertain system (1) with controller (5) is robust parameter dependent quadratically stable with guaranteed cost when controller parameters lie in the following interval:*

$$K_p \in \left\langle K_{p0} + K_{p1}\underline{\theta}, K_{p0} + K_{p1}\overline{\theta} \right\rangle$$
$$K_i \in \left\langle K_{i0} + K_{i1}\underline{\theta}, K_{i0} + K_{i1}\overline{\theta} \right\rangle$$

and rates of $\dot{\theta}$, $\dot{\xi}$ are given by (2) and (9) if there exists a positive definite matrix $P(\theta, \xi) > 0$ matrices N_k, $k = 1, 2, \dots, 6$, positive definite (semidefinite) matrices Q, S and positive definite matrix R such that inequality (15) hold.

Note that (15) holds if it holds for all $i = 1, 2, \dots, N$ vertices and for $\underline{\theta}$, $\overline{\theta}$.

Case 3.2. *Controller parameters $K_p(\theta)$, $K_i(\vartheta)$ change independently.*
In this case we assume that controller parameters change independently from each other. Using the same approach as in the first case only instead of Equation (13) we have substituted:

$$v^T \begin{bmatrix} 2N_4^T \\ 2N_5^T \\ 2N_6^T \end{bmatrix} \begin{bmatrix} -K_d C_d & -K_c(\theta, \vartheta) & I_m \end{bmatrix} v = 0 \tag{16}$$

where

$$K_c(\theta, \vartheta) = K_{p0} C_p + K_{i0} C_i + K_{p1} C_p \theta + K_{i1} C_i \vartheta \tag{17}$$

Summarizing (4), (12), (13) and (16) one obtains the Bellman-Lyapunov function for the second case (17) in the form

$$B_{e2} = v^T V_e(\xi, \theta, \vartheta) v \leq 0 \tag{18}$$

Due to that (18) is convex with respect to ξ, θ, ϑ one can rewrite (18) as follows:

$$V_e(\xi, \theta, \vartheta) = \sum_{i=1}^{N} V_i \xi_i \tag{19}$$

and

$$V_i = V_{0i} + V_{1i}\theta + V_{2i}\vartheta \leq 0, \quad i = 1, 2, \ldots, N \tag{20}$$

$$\begin{aligned} V_{0i} &= \{v_{0kl}(i)\}_{3\times 3} \\ V_{1i} &= \{v_{1kl}(i)\}_{3\times 3} \\ V_{2i} &= \{v_{2kl}(i)\}_{3\times 3} \end{aligned}$$

$$\begin{aligned}
v_{011}(i) &= S + N_1^T N_1 - N_4^T K_d C_d - C_d^T K_d^T N_4 \\
v_{111}(i) &= 0,\ v_{211}(i) = 0 \in R^{n\times n} \\
v_{012}(i) &= P_{0i} - N_4^T (K_{p0} C_p + K_{i0} C_i) - C_d^T K_d^T N_5 - N_1^T A_i + N_2 \\
v_{112}(i) &= P_{1i} - N_4^T K_{p1} C_p,\ v_{212}(i) = P_{2i} - N_4^T K_{i2} C_i \\
v_{013}(i) &= N_3 + N_4^T - C_d^T K_d^T N_6 - N_1^T B_i \\
v_{113}(i) &= 0 \\
v_{213}(i) &= 0 \in R^{n\times m} \\
v_{022}(i) &= -N_5^T (K_{p0} C_p + K_{i0} C_i) - (K_{p0} C_p + K_{i0} C_i)^T N_5 \\
&\quad - N_2^T A_i - A_i^T N_2 + Q + M_{0i} \\
v_{122}(i) &= -N_5^T K_{p1} C_p N_5 + M_{1i} \\
v_{222}(i) &= -N_5^T K_{1i} C_i - C_i^T K_{i1}^T N_5 + M_{21} \\
v_{023}(i) &= N_5^T - (K_{p0} C_p + K_{i0} C_i)^T N_6 - N_2^T B_i - A_i^T N_3 \\
v_{123}(i) &= -C_p^T K_{p1}^T N_6,\ v_{223}(i) = -C_i^T K_{i1}^T N_6 \\
v_{033}(i) &= -N_3^T B_i - B_i^T N_3 + R + N_6^T + N_6 \\
v_{133}(i) &= 0 \\
v_{233}(i) &= 0 \in R^{m\times m}
\end{aligned}$$

For the second case Lyapunov matrix (11) is as follows:

$$\begin{aligned}
&P(\xi, \theta, \vartheta) = P_0(\xi) + P_1(\xi)\theta + P_2(\xi)\vartheta \\
&P_j(\xi) = \sum_{i=1}^{N} P_{ji}\xi,\ j = 0, 1, 2 \\
&P\left(\dot{\xi}, \dot{\theta}, \dot{\vartheta}\right) = \sum_{i=1}^{N} \left(M_{0i} + M_{1i}\theta + M_{2i}\vartheta\right) \xi_i \\
&M_{0i} = \sum_{l=1}^{N} P_{0l}\dot{\xi}_l + P_{1i}\dot{\theta} + P_{2i}\dot{\vartheta} \\
&M_{1i} = \sum_{l=1}^{N} P_{1l}\dot{\xi}_l,\ M_{2i} = \sum_{l=1}^{N} P_{2l}\dot{\xi}_l
\end{aligned}$$

For the second case the obtained results are summarized in the following theorem.

Theorem 3.2. *Uncertain system (1) with controller (6), (17) is robust parameter dependent quadratically stable with guaranteed cost for all controller parameters*

$$K_p \in \left\langle K_{p0} + K_{p1}\underline{\theta}, K_{p0} + K_{p1}\overline{\theta} \right\rangle$$
$$K_i \in \left\langle K_{i0} + K_{i1}\underline{\vartheta}, K_{i0} + K_{i1}\overline{\vartheta} \right\rangle$$

and rate of $\dot{\theta}$, $\dot{\vartheta}$ (9) if there exists a positive definite matrix $P(\xi, \theta, \vartheta) > 0$ matrices N_k, $k = 1, 2, \ldots, 6$, positive definite (semidefinite) matrices S, Q and definite matrix R such that inequality (20) holds for all $i = 1, 2, \ldots, N$ and corners of θ, ϑ and their rates.

4. **Example.** Consider the following augmented (I-part of the controller) uncertain system:

$$A_1 = \begin{bmatrix} -0.23 & 0.25 & 0 \\ 0.1 & -0.5 & 0 \\ 0 & 1 & 0 \end{bmatrix} \qquad B_1 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$
$$A_2 = \begin{bmatrix} -0.1 & 0.2 & 0 \\ 0.09 & -0.55 & 0 \\ 0 & 1 & 0 \end{bmatrix} \qquad B_2 = \begin{bmatrix} 0 \\ 0.9 \\ 0 \end{bmatrix}$$
$$C_p = C_d = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad C_i = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Under the following parameters: performance $Q = q * I$, $q = 0.001$, $S = s * I$, $s = 0$, $R = r * I_r$, $r = 1$, rate of change $\max \dot{\theta} = \max \dot{\vartheta} = 0.5/\text{sec}$, $\max \dot{\xi} = 0.01/\text{sec}$ and PID controller

$$R(s) = K_p + \frac{K_i}{s} + K_d s$$

for the two cases the following results are obtained
$\theta, \vartheta \in \langle -0.1, 1 \rangle$

1.
$$\begin{aligned} &K_p \in \langle -0.7841, -1.5683 \rangle, \\ &K_i \in \langle -0.7, -1.9235 \rangle, \\ &K_d = -0.0962 \end{aligned}$$

2.
$$\begin{aligned} &K_p \in \langle -0.922, -1.1518 \rangle, \\ &K_i \in \langle -0.8777, -1.0425 \rangle, \\ &K_d = -0.0753 \end{aligned}$$

$\max \dot{\theta} = \max \dot{\vartheta} = 0$:

1.
$$\begin{aligned} &K_p \in \langle -0.9014, -1.1319 \rangle, \\ &K_i \in \langle -0.6739, -0.8999 \rangle, \\ &K_d = -0.1363 \end{aligned}$$

2.
$$\begin{aligned} &K_p \in \langle -0.4674, -1.8402 \rangle, \\ &K_i \in \langle -0.4854, -1.62154 \rangle, \\ &K_d = -0.0524 \end{aligned}$$

$\underline{\theta} = \underline{\vartheta} = -1$, $\overline{\theta} = \overline{\vartheta} = 1$

1.

$$\begin{aligned} &K_p \in \langle -0.6532, -0.7462 \rangle, \\ &K_i \in \langle -0.6887, -0.7929 \rangle, \\ &K_d = -0.0514 \end{aligned}$$

2.

$$\begin{aligned} &K_p \in \langle -0.9468, -1.0138 \rangle, \\ &K_i \in \langle -0.7862, -0.879 \rangle, \\ &K_d = -0.1345 \end{aligned}$$

$\underline{\theta} = \underline{\vartheta} = 0$, $\overline{\theta} = \overline{\vartheta} = 1$

1.

$$\begin{aligned} &K_p \in \langle -0.6301532, -2.697 \rangle, \\ &K_i \in \langle -0.6079, -1.0394 \rangle, \\ &K_d = -0.1056 \end{aligned}$$

2.

$$\begin{aligned} &K_p \in \langle -1.277, -1.5817 \rangle, \\ &K_i \in \langle -0.8314, -0.946 \rangle, \\ &K_d = -0.234 \end{aligned}$$

$\underline{\theta} = \underline{\vartheta} = -1$, $\overline{\theta} = \overline{\vartheta} = 0$

1.

$$\begin{aligned} &K_p \in \langle -0.7203, -1.4865 \rangle, \\ &K_i \in \langle -0.7024, -0.9447 \rangle, \\ &K_d = -0.0777 \end{aligned}$$

2.

$$\begin{aligned} &K_p \in \langle -0.9702, -1.167 \rangle, \\ &K_i \in \langle -0.8707, -0.9583 \rangle, \\ &K_d = -0.1073 \end{aligned}$$

Note that within the obtained controller parameters changes, the controller parameters may change with rate of $\max\dot{\theta} = \max\dot{\vartheta} = 0.5/\mathrm{sec}$ without violation of closed loop robust stability. Plant parameters may change with rate of $\max\dot{\xi} = 0.01/\mathrm{sec}$. The designer could use the above new possibilities to increase the performance of the closed loop system. One can observe that in the case of simultaneously controller parameters changes (case 1.) the obtained interval is larger than independent controller parameters changes.

5. **Conclusion.** This paper is devoted to developing a novel robust controller design procedure for polytopic uncertain continuous-time systems in the frame of H_2 – guaranteed cost and parameter dependent quadratic stability. In this paper the obtained design procedure allows design of robust static output/state feedback with PID structure. In addition, the design procedure is convex regarding to the auxiliary parameters (θ, ϑ) which may decrease the conservativeness of the controller design procedure. The obtained controller parameters (K_p, K_i) and their possible interval changes do not violate the robust stability condition and performance of closed loop system. There are two design approaches: controller parameters changes as a function of auxiliary parameter θ or controller parameters changes independently of each other. Controller designer should use obtained results for increasing the quality of closed-loop dynamic process via changing

(which direction is a future research) the controller parameters in the obtained interval without violating the stability and obtained quality of closed-loop systems. The obtained design results of their properties and effectiveness are illustrated on the simple example with five different auxiliary parameter values from which the robust controller designer should choose one of them.

Acknowledgement. The work has been supported by the Slovak Scientific Grant Agency, Grant No. 1/0475/16. The authors also gratefully acknowledge the helpful comments and suggestions of the reviewers, which have improved the presentation.

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