

Multi-Parameter Dependent Lyapunov Functions for the Stability Analysis of Parameter-Dependent LTI Systems

X. Zhang and P. Tsiotras

School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA, 30332-0150, USA

P.-A. Bliman

INRIA Rocquencourt B.P. 105, 78153 Le Chesnay Cedex, FRANCE.

Abstract—In this paper it is shown that robust stability of multi-parameter affinely-dependent LTI systems is equivalent to the existence of a multi-parameter polynomially-dependent quadratic Lyapunov function of known, bounded degree in terms of the system parameters. Testing the stability of multi-parameter dependent LTI systems over a compact, connected set can be cast in terms of two finite-dimensional linear matrix inequalities (LMIs).

I. INTRODUCTION

The objective of this paper is to find computable, non-conservative conditions for checking the asymptotic stability of parameter-dependent LTI (PDLTI) systems that depend affinely on a parameter vector $\rho := (\rho_1, \dots, \rho_m)^T \in \Omega \subset \mathbb{R}^m$, of the form

$$\dot{x} = A(\rho)x, \quad A(\rho) := \sum_{i=0}^m \rho_i A_i, \quad \rho_0 = 1, \quad (1)$$

where $A_i \in \mathbb{R}^{n \times n}$, ($i = 0, 1, 2, \dots, m$). It is assumed that Ω is a compact and connected subset of \mathbb{R}^m . Stability criteria for PDLTI systems can be derived by searching for a suitable Lyapunov function whose time derivative remains negative along the trajectories of (1). In general, a quadratic Lyapunov function $x^T P x$ is postulated. The Lyapunov matrix P is either constant or parameter dependent. If P is constant, quadratic stability for (1) is ensured. Quadratic stability is a rather strong form of robust stability [1]. It leads to conservative results, especially if it is known that ρ is constant. Stability conditions closer to being necessary can be derived by using a parameter-dependent Lyapunov matrix instead, i.e., $P = P(\rho)$; see, for example [2], [3], [4], [5], [6]. Nonetheless, sufficient and necessary conditions result only if the correct parameter dependence of the Lyapunov matrix is used. Till recently, this “correct” form of the Lyapunov matrix $P(\rho)$ leading to non-conservative conditions has eluded the researchers in the field, except some very special cases [7], [8]. In fact, it is well known that robust stability analysis of multi-parameter dependent LTI systems is, in general, an NP-hard problem [9], [10], [11].

A very important recent result by Bliman [12] states that parameter-dependent LMIs admit polynomial solutions, provided they are feasible for each parameter value. This result paved the way to *necessary* Lyapunov-based conditions for parameter-varying and PDLTI systems. In [13], in particular, the author was able to show that the stability of (1) can be analyzed *without conservatism* via the use of *polynomial* parameter-dependent

quadratic (PPQD) Lyapunov functions. However, the degree of the polynomial dependence in [13] is not known a priori. A similar result was obtained independently around the same time in [14] using a different approach. For the single-parameter case ($m = 1$), in particular, Refs. [14], [15] provided an upper bound for the polynomial dependence of the matrix $P(\rho)$. When the parameter is known to belong inside a compact interval, the stability of the matrix $A(\rho) = A_0 + \rho A_1$ can be tested through a pair of linear matrix inequalities (LMIs) without conservatism. Moreover, in general, the LMI conditions in [15] are computationally more efficient than the ones given in [13].

The problem of robust stability of PDLTI systems has also been addressed in the recent work of Chesi et al [16]. Therein the authors show that homogeneous polynomially parameter-dependent quadratic Lyapunov functions can be used to characterize robust stability of polytopic linear models. For systems affected by *polynomial* time-invariant uncertainty Chesi [16] has also provided computationally attractive LMI conditions, albeit these conditions are not Lyapunov based.

This paper contains two contributions. First, we extend the results of [15] to the case of multi-parameter dependent LTI systems of the form (1). Specifically, we show that the polynomial parameter-dependent Lyapunov function matrix of degree M

$$P(\rho) = \sum_{|k|=0}^M \rho_1^{k_1} \cdots \rho_m^{k_m} P_{k_1, \dots, k_m}, \quad (2)$$

where $M \leq \frac{1}{2}n(n+1) - 1$ can be used to derive a nonconservative (i.e., necessary and sufficient) stability condition for (1). Second, we provide convex conditions for stability when the parameter vector belongs to a compact and connected set. Finally, the results of this paper can be considered as an improvement over the results of [13] by providing upper bounds on the polynomial degree of the Lyapunov function that *characterizes* stability of LTI multi-parameter dependent systems.

II. MATHEMATICAL PRELIMINARIES

Let a multi-variable polynomial $\pi(\rho)$, given by

$$\pi(\rho) = \sum_{|k|=0}^N \rho_1^{k_1} \cdots \rho_m^{k_m} p_{k_1, \dots, k_m},$$

where $\rho := (\rho_1, \rho_2, \dots, \rho_m)^T \in \mathbb{R}^m$ and $|k| := k_1 + k_2 + \dots + k_m$ with $k_i \in \mathbb{N}_0$.

Definition 1: The *multi-parameter* degree of $\pi(\rho)$ with respect to the vector ρ is defined as $\deg \pi(\rho) := \max\{k_1 + \dots + k_m, p_{k_1, \dots, k_m} \neq 0\}$. Similarly, the *single-parameter* degree

Postdoctoral Research Fellow. E-mail: xz37@mail.gatech.edu. Tel: +1-404-385-2790.

Professor. E-mail: p.tsiotras@ae.gatech.edu. Tel: +1-404-894-9526. Corresponding author.

Email: pierre-alexandre.bliman@inria.fr. Tel: +33-1-39-63-55-68.

of $\pi(\rho)$ with respect to the scalar parameter ρ_i is defined as $\deg_i \pi(\rho) := \max\{k_i, p_{\dots, k_i, \dots} \neq 0\}$. \square

For a matrix $\Pi(\rho) \in \mathbb{R}^{n \times n}$ with polynomial elements we define similarly the multi-parameter degree and the single-parameter degree of $\Pi(\rho)$ as $\deg \Pi(\rho) := \max_{1 \leq q, \ell \leq n} \deg \Pi_{(q, \ell)}(\rho)$ and $\deg_i \Pi(\rho) := \max_{1 \leq q, \ell \leq n} \deg_i \Pi_{(q, \ell)}(\rho)$, respectively. The following result, adapted from the single-parameter case [15], is therefore immediate. Note that in the following $\mathcal{N}(A)$ denotes the null space of the matrix A .

Lemma 2.1 ([14]): Given matrices $A_i \in \mathbb{R}^{n \times n}$, ($i = 0, 1, 2, \dots, m$) and $\rho = (\rho_1, \rho_2, \dots, \rho_m)^\top \in \mathbb{R}^m$, let $\pi(\rho) := \det \sum_{i=0}^m \rho_i A_i$. Then $\deg \pi(\rho) \leq n$. If $\dim \mathcal{N}(A_i) = r_i$ then $\deg_i \pi(\rho) \leq n - r_i$. Moreover, if $\dim[\bigcap_{i=1}^m \mathcal{N}(A_i)] = r$, then $\deg \pi(\rho) \leq n - r$. \square

The next result deals with the multi- and single-parameter degrees of the adjoint of the matrix $A(\rho) = A_0 + \rho_1 A_1 + \dots + \rho_m A_m$.

Corollary 2.1: Let matrices $A_i \in \mathbb{R}^{n \times n}$, ($i = 0, 1, 2, \dots, m$) and $\rho = (\rho_1, \rho_2, \dots, \rho_m)^\top \in \mathbb{R}^m$. Assume that $\dim \mathcal{N}(A_i) = r_i$ and $\dim[\bigcap_{i=1}^m \mathcal{N}(A_i)] = r$. Then

$$\deg \text{Adj}\left(\sum_{j=0}^m \rho_j A_j\right) \leq \min\{n-1, n-r\} \quad (3)$$

and

$$\deg_i \text{Adj}\left(\sum_{j=0}^m \rho_j A_j\right) \leq \min\{n-1, n-r_i\}, \quad (4)$$

for all $i = 1, 2, \dots, m$. \square

Equation (3) implies, in particular, that

$$\text{Adj}\left(\sum_{j=0}^m \rho_j A_j\right) = \sum_{|k|=0}^{\min\{n-1, n-r\}} \rho_1^{k_1} \dots \rho_m^{k_m} N_{k_1, \dots, k_m}$$

for some constant matrices $N_{k_1, \dots, k_m} \in \mathbb{R}^{n \times n}$.

Given a square matrix $P \in \mathbb{R}^{n \times n}$, let $\text{vec}(P) \in \mathbb{R}^{n^2}$ denote the usual operation that stacks the columns of the matrix P on top of each other [18]. In case the matrix P is symmetric, $\text{vec}(P)$ contains repeated entries. In order to remove any repetitions we introduce the following alternative.

Definition 2 ([19]): Given a symmetric matrix $P = P^\top \in \mathbb{R}^{n \times n}$, let $\text{svec}(P) := (P_{11}, \dots, P_{n1}, P_{22}, \dots, P_{n2}, \dots, P_{nn})^\top \in \mathbb{R}^{\frac{1}{2}n(n+1)}$.

Note that $\text{svec}(P)$ consists of all the elements of $\text{vec}(P)$ without repetitions.

For every symmetric matrix $P = P^\top \in \mathbb{R}^{n \times n}$, there exists a unique full column rank matrix $D_n \in \mathbb{R}^{n^2 \times \frac{1}{2}n(n+1)}$ called *the duplication matrix*, such that $\text{vec}(P) = D_n \text{svec}(P)$. Moreover, the pseudo-inverse of D_n satisfies $\text{svec}(P) = D_n^+ \text{vec}(P)$, $D_n^+ D_n = I_{\frac{1}{2}n(n+1)}$ and $\text{rank } D_n = \text{rank } D_n^+ = \frac{1}{2}n(n+1)$; see, for instance, [20], [19]. Note, in particular, that D_n has always full column rank. Subsequently, $D_n^+ = (D_n^\top D_n)^{-1} D_n^\top$.

Definition 3 ([19]): Given $A \in \mathbb{R}^{n \times n}$, let \hat{A} denote the matrix of dimension $\frac{1}{2}n(n+1) \times \frac{1}{2}n(n+1)$, defined by

$$\hat{A} := D_n^+(A \oplus A)D_n, \quad (5)$$

where $A \oplus A = A \otimes I_n + I_n \otimes A$ is the Kronecker sum of a matrix with itself. \square

Lemma 2.2 ([20], [19]): Let $A \in \mathbb{R}^{n \times n}$ and \hat{A} as in Definition 3. The eigenvalues of \hat{A} are the $\frac{1}{2}n(n+1)$ numbers $\lambda_i + \lambda_j$, ($1 \leq j \leq i \leq n$) where λ_i, λ_j are the eigenvalues of A . \square

The following is immediate from Lemma 2.2.

Corollary 2.2: Let a matrix $A \in \mathbb{R}^{n \times n}$ be Hurwitz. Then the following hold:

- (i) \hat{A} is Hurwitz.
- (ii) $\det \hat{A} \neq 0$. \square

It is clear that if $A(\rho) = \sum_{i=0}^m \rho_i A_i$ then $\hat{A}(\rho) = \sum_{i=0}^m \rho_i \hat{A}_i$. Moreover, the following is true.

Lemma 2.3 ([15]): Let $A \in \mathbb{R}^{n \times n}$ with $\dim \mathcal{N}(A) = r$. Then $\hat{r} := \dim \mathcal{N}(\hat{A}) \geq \frac{1}{2}r(r+1)$. \square

III. MAIN RESULTS

A. A Class of Polynomial Parameter-Dependent Lyapunov Matrices

In the following, Ω denotes any subset of \mathbb{R}^m . The following theorem shows that the existence of a parameter-dependent, polynomial Lyapunov matrix of a given degree is equivalent to the fact that $A(\rho)$ is Hurwitz for each $\rho \in \Omega$.

Theorem 3.1: Let matrices $A_i \in \mathbb{R}^{n \times n}$, ($i = 0, 1, 2, \dots, m$), and $\rho = (\rho_1, \rho_2, \dots, \rho_m)^\top \in \Omega \subset \mathbb{R}^m$. Assume that $\dim[\bigcap_{i=1}^m \mathcal{N}(\hat{A}_i)] = \hat{r}$. Then the following two statements are equivalent:

- (i) $A(\rho) = \sum_{i=0}^m \rho_i A_i$ is Hurwitz for all $\rho \in \Omega$.
- (ii) There exist matrices $P_{k_1, k_2, \dots, k_m} \in \mathbb{R}^{n \times n}$, where $k_i \in \mathbb{N}_0$, ($i = 1, \dots, m$), such that for all $\rho \in \Omega$,

$$A(\rho)P(\rho) + P(\rho)A^\top(\rho) < 0, \quad P(\rho) > 0, \quad (6)$$

where,

$$P(\rho) = \sigma(\rho) \sum_{|k|=0}^M \rho_1^{k_1} \dots \rho_m^{k_m} P_{k_1, \dots, k_m} \quad (7)$$

and where $M = \min\{\frac{1}{2}n(n+1) - 1, \frac{1}{2}n(n+1) - \hat{r}\}$ and $\sigma(\rho) := -\text{sign}(\det \hat{A}(\rho))$. Equivalently,

$$\deg P(\rho) \leq \min\{\frac{1}{2}n(n+1) - 1, \frac{1}{2}n(n+1) - \hat{r}\}.$$

Moreover, if $\dim \mathcal{N}(A_i) = r_i$ then

$$\deg_i P(\rho) \leq \frac{1}{2}(n - r_i)(n + r_i + 1). \quad \square$$

Proof: (ii) \Rightarrow (i): It is obvious.

(i) \Rightarrow (ii): Since $A(\rho)$ is Hurwitz for all $\rho \in \Omega$, it follows from Corollary 2.2 that $\det \hat{A}(\rho) \neq 0$ for all $\rho \in \Omega$. Consider the parameter-dependent, positive definite matrix

$$Q(\rho) := |\det \hat{A}(\rho)| I_n > 0. \quad (8)$$

Since $A(\rho)$ is Hurwitz for all $\rho \in \Omega$, the following Lyapunov equation has a unique, positive definite solution $P(\rho) > 0$ for each $\rho \in \Omega$ [21]

$$A(\rho)P(\rho) + P(\rho)A^\top(\rho) + |\det \hat{A}(\rho)| I_n = 0. \quad (9)$$

The solution to this Lyapunov equation yields

$$\text{svec}(P) = -|\det \hat{A}(\rho)| \hat{A}^{-1}(\rho) \text{svec}(I_n)$$

Therefore, $\text{svec}(P) = \sigma(\rho)\text{Adj}(\sum_{i=0}^m \rho_i \hat{A}_i) \text{svec}(I_n)$. From Corollary 2.1 one obtains that

$$\deg \text{Adj}\left(\sum_{j=0}^m \rho_j \hat{A}_j\right) \leq \min\left\{\frac{1}{2}n(n+1) - 1, \frac{1}{2}n(n+1) - \hat{r}\right\}$$

If $\dim \mathcal{N}(A_i) = r_i$, from Lemma 2.3 one has that $\dim \mathcal{N}(\hat{A}_i) = \hat{r}_i \geq \frac{1}{2}r_i(r_i + 1)$. Therefore, $\frac{1}{2}n(n+1) - \hat{r}_i \leq \frac{1}{2}(n - r_i)(n + r_i + 1)$. It follows from Corollary 2.1 that

$$\deg_i \text{Adj}\left(\sum_{j=0}^m \rho_j \hat{A}_j\right) \leq \min\left\{\frac{1}{2}n(n+1) - 1, \frac{1}{2}(n - r_i)(n + r_i + 1)\right\}.$$

The result follows from the fact that the map $\text{svec}(\cdot) : \mathbb{R}^{n \times n} \rightarrow \mathbb{R}^{\frac{1}{2}n(n+1)}$ is one-to-one and thus invertible over the space of symmetric matrices. ■

Remark 1: Note that when Ω is connected then $\sigma(\rho)$ has the same sign for all $\rho \in \Omega$ and (7) reduces to

$$P(\rho) = \sum_{|k|=0}^M \rho_1^{k_1} \dots \rho_m^{k_m} P_{k_1, \dots, k_m}, \quad \forall \rho \in \Omega. \quad (10)$$

Example 1: This example is taken from [22]. Consider the matrix $A(\rho) = A_0 + \rho_1 A_1 + \rho_2 A_2$, where

$$A_0 = \begin{bmatrix} -2 & 0 & -1 \\ 0 & -3 & 0 \\ -1 & -1 & -4 \end{bmatrix}, \quad A_1 = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 1 \end{bmatrix} \quad (11)$$

$$A_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \end{bmatrix}.$$

The exact robust stability region for this problem is $(-\infty, 1.75) \times (-\infty, 3)$ (see [22]). Reference [23] suggests an algorithm to calculate this stability domain exactly. Here we compute the stability domain of (11) using Theorem 3.1.

The elements of the parameter-dependent Lyapunov matrix $P(\rho) \in \mathbb{R}^{3 \times 3}$ can be computed as follows

$$\begin{aligned} P_{11} &= -16\rho_2^2\rho_1^3 - 8592\rho_1 - 6720\rho_2 - 96\rho_2^3 + 56\rho_2^2\rho_1 - 8\rho_2^3\rho_1^2 \\ &\quad + 9792 - 1456\rho_2\rho_1^2 + 128\rho_2\rho_1^3 + 2496\rho_1^2 \\ &\quad + 5456\rho_2\rho_1 - 240\rho_1^3 + 1440\rho_2^2 - 1032\rho_2^2\rho_1 + 232\rho_2^2\rho_1^2, \\ P_{21} &= -16\rho_2^2\rho_1^3 - 1008\rho_1 - 936\rho_2 - 24\rho_2^3 + 32\rho_2^3\rho_1 - 8\rho_2^3\rho_1^2 \\ &\quad + 648 - 568\rho_2\rho_1^2 + 64\rho_2\rho_1^3 + 408\rho_1^2 + 1440\rho_2\rho_1 \\ &\quad - 48\rho_1^3 + 312\rho_2^2 - 464\rho_2^2\rho_1 + 168\rho_2^2\rho_1^2 \\ P_{22} &= -16\rho_2^2\rho_1^3 - 7152\rho_1 - 2592\rho_2 - 48\rho_2^3 + 40\rho_2^3\rho_1 - 8\rho_2^3\rho_1^2 \\ &\quad - 936\rho_2\rho_1^2 + 96\rho_2\rho_1^3 + 2728\rho_1^2 + 2808\rho_2\rho_1 - 336\rho_1^3 \\ &\quad + 528\rho_2^2 - 536\rho_2^2\rho_1 + 168\rho_2^2\rho_1^2 + 5976, \\ P_{31} &= 16\rho_2^2\rho_1^3 + 3984\rho_1 + 1680\rho_2 + 24\rho_2^2 - 32\rho_2^3\rho_1 + 8\rho_2^3\rho_1^2 \\ &\quad - 2448 + 1072\rho_2\rho_1^2 - 128\rho_2\rho_1^3 - 1776\rho_1^2 - 2624\rho_2\rho_1 \\ &\quad + 240\rho_1^3 - 360\rho_2^2 + 528\rho_2^2\rho_1 - 184\rho_2^2\rho_1^2 \\ P_{32} &= 16\rho_2^2\rho_1^3 + 912\rho_1 + 1200\rho_2 + 48\rho_2^2 - 40\rho_2^3\rho_1 + 8\rho_2^3\rho_1^2 \\ &\quad - 792 + 504\rho_2\rho_1^2 - 64\rho_2\rho_1^3 - 360\rho_1^2 - 1336\rho_2\rho_1 \\ &\quad + 48\rho_1^3 - 456\rho_2^2 + 464\rho_2^2\rho_1 - 152\rho_2^2\rho_1^2, \\ P_{33} &= -16\rho_2^2\rho_1^3 - 5520\rho_1 - 3360\rho_2 - 48\rho_2^3 + 40\rho_2^3\rho_1 - 8\rho_2^3\rho_1^2 \\ &\quad + 4896 - 1200\rho_2\rho_1^2 + 128\rho_2\rho_1^3 + 2016\rho_1^2 + 3568\rho_2\rho_1 \\ &\quad - 240\rho_1^3 + 720\rho_2^2 - 696\rho_2^2\rho_1 + 200\rho_2^2\rho_1^2. \end{aligned}$$

The matrix inequalities (6) were checked over a fine grid in the parameter space ρ_1 - ρ_2 . The results are shown in Fig. 1. Region I denotes the domain where both inequalities were satisfied. On the

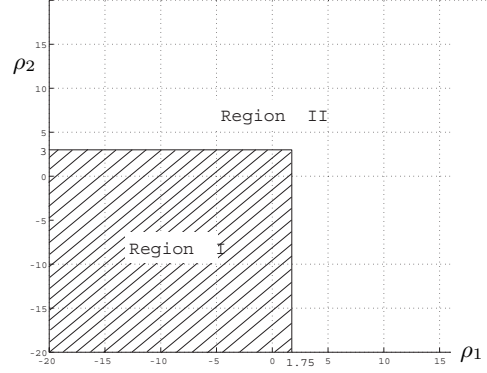


Fig. 1. Stability region for Example 1.

other hand, in Region II at least one of the matrix inequalities in (6) was violated. The results coincide with those of [22] and [23].

IV. LMI CONDITIONS

A. An Alternative Expression for the Parameter-Dependent Lyapunov Matrix

Theorem 3.1 provides Lyapunov-based conditions for checking the stability of (1). Condition (6) represents a parameterized family of matrix inequalities. It is of interest to develop finite-dimensional counterparts to (6). In this section, and in preparation for the derivation of such conditions, we present a more convenient form for expressing a polynomially-dependent matrix. The notation and results below closely follow those of [13].

To this end, let the vector $z^{[q]} := (1, z, z^2, \dots, z^{q-1})^\top \in \mathbb{R}^q$. In the sequel we will often use the shorthand notation $\otimes_{i=m}^1 z_i^{[k_i]}$ to denote the product $z_m^{[k_m]} \otimes \dots \otimes z_1^{[k_1]}$. Next, notice that the matrix $P(\rho)$ in (7) can be written as follows,

$$P(\rho) = \sum_{|k|=0}^{k_1=\bar{k}_1, \dots, k_m=\bar{k}_m} \rho_1^{k_1} \dots \rho_m^{k_m} P_{k_1, \dots, k_m}, \quad (12)$$

where $\deg_i P(\rho) = \bar{k}_i \leq \min\{\frac{1}{2}n(n+1) - 1, \frac{1}{2}(n - r_i)(n + r_i + 1)\}$ and where $r_i = \dim \mathcal{N}(A_i)$. Let $\bar{\alpha}_i := \lceil \frac{\bar{k}_i}{2} \rceil + 1$. Then the parameter-dependent matrix in (12) can be expressed as

$$P(\rho) = \left(\otimes_{i=m}^1 \rho_i^{[\bar{\alpha}_i]} \otimes I_n \right)^\top P_\Sigma \left(\otimes_{i=m}^1 \rho_i^{[\bar{\alpha}_i]} \otimes I_n \right) \quad (13)$$

where P_Σ is a symmetric matrix of dimension $(\bar{\alpha}_1 \bar{\alpha}_2 \dots \bar{\alpha}_m n) \times (\bar{\alpha}_1 \bar{\alpha}_2 \dots \bar{\alpha}_m n)$. The matrix P_Σ can be divided into $(\bar{\alpha}_1 \bar{\alpha}_2 \dots \bar{\alpha}_m) \times (\bar{\alpha}_1 \bar{\alpha}_2 \dots \bar{\alpha}_m)$ blocks, each of dimension $n \times n$. In fact, the nonzero blocks of the matrix P_Σ are just the matrix coefficients of the polynomial matrix $P(\rho)$.

Similarly, $\rho_m^{[\bar{\alpha}_m]} \otimes \dots \otimes \rho_1^{[\bar{\alpha}_1]} \otimes I_n$ is a matrix composed of $\bar{\alpha}_1 \bar{\alpha}_2 \dots \bar{\alpha}_m$ blocks, each block having dimension $n \times n$.

The matrix P_Σ in (13) is not unique. One method for constructing a possible P_Σ is as follows.

Definition 4: Given $\bar{\alpha} := (\bar{\alpha}_1 \bar{\alpha}_2 \dots \bar{\alpha}_m)^\top \in \mathbb{N}^m$ the index function $f_{\bar{\alpha}}$ is defined as $f_{\bar{\alpha}}(\alpha_1, \alpha_2, \dots, \alpha_m) := \bar{\alpha}_1 \bar{\alpha}_2 \dots \bar{\alpha}_{m-1} \alpha_m + \bar{\alpha}_1 \bar{\alpha}_2 \dots \bar{\alpha}_{m-2} \alpha_{m-1} + \dots + \bar{\alpha}_1 \alpha_2 + \alpha_1 + 1$.

Let the square matrix \bar{P}_Σ having the same dimension as P_Σ and let $\bar{P}_{\Sigma, (i,j)}$ stand for the (i, j) block of \bar{P}_Σ . For every non-zero term $\rho_1^{k_1} \rho_2^{k_2} \dots \rho_m^{k_m} P_{k_1, k_2, \dots, k_m}$ in (12), let $\alpha_i = \lceil \frac{k_i}{2} \rceil$ and $\beta_i = \lfloor \frac{k_i}{2} \rfloor$

for $i = 1, 2, \dots, m$ and let $\bar{P}_{\Sigma, (f_1, f_2)} = P_{k_1, k_2, \dots, k_m}$, where the indices f_1 and f_2 are given by $f_1 = f_{\bar{\alpha}}(\alpha_1, \alpha_2, \dots, \alpha_m)$ and $f_2 = f_{\bar{\beta}}(\beta_1, \beta_2, \dots, \beta_m)$. Finally, let

$$P_{\Sigma} = \frac{1}{2}(\bar{P}_{\Sigma} + \bar{P}_{\Sigma}^{\top}).$$

We now turn our attention to finding a similarly convenient form for the polynomial matrix

$$R(\rho) := A(\rho)P(\rho) + P(\rho)A^{\top}(\rho). \quad (14)$$

It is desirable to express $R(\rho)$ in a form similar to that of (13). In order to achieve this we use the following results [13].

Let $\hat{J}_k := [I_k \ 0_{k \times 1}]$ and $\check{J}_k := [0_{k \times 1} \ I_k]$. It is clear that $\hat{J}_k z^{[k+1]} = z^{[k]}$ and $\check{J}_k z^{[k+1]} = z z^{[k]}$. Moreover, for any matrices $A \in \mathbb{R}^{n \times n}$ and $M \in \mathbb{R}^{p \times q}$, the following properties can be easily verified [13]:

- (i) $(z^{[k]} \otimes I_p)M = (I_k \otimes M)(z^{[k]} \otimes I_q)$
- (ii) $(z_m^{[k_m]} \otimes \dots \otimes z_1^{[k_1]} \otimes I_n)A = z_m^{[k_m]} \otimes \dots \otimes z_1^{[k_1]} \otimes A = (I_{k_1 k_2 \dots k_m} \otimes A)(z_m^{[k_m]} \otimes \dots \otimes z_1^{[k_1]} \otimes I_n)$.
- (iii) $z_m^{[k_m]} \otimes \dots \otimes z_1^{[k_1]} \otimes I_n = (\hat{J}_{k_m} \otimes \dots \otimes \hat{J}_{k_1} \otimes I_n)(z_m^{[k_m+1]} \otimes \dots \otimes z_1^{[k_1+1]} \otimes I_n)$.
- (iv) $z_m^{[k_m]} \otimes \dots \otimes z_j z^{[k_j]} \otimes \dots \otimes z_1^{[k_1]} \otimes I_n = (\hat{J}_{k_m} \otimes \dots \otimes \hat{J}_{k_j} \otimes \dots \otimes \hat{J}_{k_1} \otimes I_n)(z_m^{[k_m+1]} \otimes \dots \otimes z_1^{[k_1+1]} \otimes I_n)$.

Lemma 4.1 ([13]): Given a matrix $A(\rho) \in \mathbb{R}^{n \times n}$ as in (1) and a symmetric matrix $P(\rho) \in \mathbb{R}^{n \times n}$ as in (13), let $R(\rho) = A^{\top}(\rho)P(\rho) + P(\rho)A(\rho)$. Then

$$R(\rho) = \left(\otimes_{i=m}^1 \rho_i^{[\bar{\alpha}_i+1]} \otimes I_n \right)^{\top} R_{\Sigma} \left(\otimes_{i=m}^1 \rho_i^{[\bar{\alpha}_i+1]} \otimes I_n \right) \quad (15)$$

and $R_{\Sigma} := H_{\Sigma}^{\top} P_{\Sigma} F_{\Sigma} + F_{\Sigma}^{\top} P_{\Sigma} H_{\Sigma}$ where, $H_{\Sigma} := \hat{J}_{\bar{\alpha}_m} \otimes \dots \otimes \hat{J}_{\bar{\alpha}_1} \otimes I_n$, and $F_{\Sigma} := \hat{J}_{\bar{\alpha}_m} \otimes \dots \otimes \hat{J}_{\bar{\alpha}_1} \otimes A_0 + \sum_{i=1}^m \hat{J}_{\bar{\alpha}_m} \otimes \dots \otimes \hat{J}_{\bar{\alpha}_{i+1}} \otimes \hat{J}_{\bar{\alpha}_i} \otimes \hat{J}_{\bar{\alpha}_{i-1}} \otimes \dots \otimes \hat{J}_{\bar{\alpha}_1} \otimes A_i$. \square

The important observation here is that, for given A_i , $i = 1, 2, \dots, m$, the matrix R_{Σ} depends linearly on P_{Σ} .

B. Stability Conditions in Terms of LMIs

In this section, we express the infinite-dimensional matrix inequalities $P(\rho) > 0$ and $R(\rho) < 0$ into a pair of finite-dimensional, linear matrix inequalities. The following lemma will be helpful in this context.

Lemma 4.2 ([5]): Let matrices $Q = Q^{\top}$, F , and a compact subset of real matrices \mathcal{H} be given. The following statements are equivalent:

- (i) For each $H \in \mathcal{H}$

$$\xi^{\top} Q \xi < 0, \quad \forall \xi \neq 0 \text{ such that } HF\xi = 0. \quad (16)$$

- (ii) There exist $\Theta = \Theta^{\top}$ such that

$$Q + F^{\top} \Theta F < 0, \quad N_H^{\top} \Theta N_H \geq 0, \quad \forall H \in \mathcal{H},$$

where N_H denotes a matrix whose columns form a basis for the null space of H . \square

Given an integer $n \geq 2$ and the vector $K = (k_1, k_2, \dots, k_m)^{\top} \in \mathbb{N}^m$, let the matrices $C_{K,i} := \check{J}_m \otimes \check{J}_{m-1} \otimes \dots \otimes \check{J}_{i+1} \otimes \check{J}_{k_i-1} \otimes \check{J}_{i-1} \otimes \dots \otimes \check{J}_1 \otimes I_n$ and $J_{K,i} := \check{J}_m \otimes \check{J}_{m-1} \otimes \dots \otimes \check{J}_{i+1} \otimes \check{J}_{k_i-1} \otimes \check{J}_{i-1} \otimes \dots \otimes \check{J}_1 \otimes I_n$, where \check{J}_i , ($i = 1, \dots, m$) stands for either \hat{J}_{k_i-1} or \check{J}_{k_i-1} . Each matrix $C_{K,i}$ and $J_{K,i}$ is of dimension $q \times \ell$ where

$q = (k_1 - 1)(k_2 - 1) \dots (k_m - 1)n$ and $\ell = k_1 k_2 \dots k_m n$. Moreover, since \check{J}_i can be either \hat{J}_{k_i-1} or \check{J}_{k_i-1} , there are 2^{m-1} combinations for $C_{K,i}$ and $J_{K,i}$ for each i . Enumerating these matrices by $C_{K,i}^j$ and $J_{K,i}^j$, ($j = 1, 2, \dots, 2^{m-1}$) we introduce the matrices \mathcal{C}_K , \mathcal{J}_K and $\Delta_K(\rho)$ as follows $\mathcal{C}_K := [C_{K,1}^1, C_{K,1}^2, \dots, C_{K,1}^{2^{m-1}}, C_{K,2}^1, \dots, C_{K,i}^j, \dots, C_{K,m}^{2^{m-1}}]$ and $\mathcal{J}_K = [J_{K,1}^1, J_{K,1}^2, \dots, J_{K,1}^{2^{m-1}}, J_{K,2}^1, \dots, J_{K,i}^j, \dots, J_{K,m}^{2^{m-1}}]$, and $\Delta_K(\rho) := \text{diag}[\rho_1 I_{q 2^{m-1}}, \dots, \rho_m I_{q 2^{m-1}}]$. It can be readily verified that the matrices \mathcal{C}_K and \mathcal{J}_K have dimension $2^{m-1} m q \times \ell$ and $\Delta_K(\rho)$ has dimension $2^{m-1} m q \times 2^{m-1} m q$, respectively.

Lemma 4.3: Let $K = (k_1, k_2, \dots, k_m)^{\top} \in \mathbb{N}^m$ and define the matrices \mathcal{J}_K , \mathcal{C}_K and $\Delta_K(\rho)$ as before. Let the sets $\mathcal{S}_1 := \{ \xi \in \mathbb{R}^{\ell} : (\mathcal{J}_K - \Delta_K(\rho)\mathcal{C}_K)\xi = 0, \xi \neq 0, \text{ some } \rho \in \mathbb{R}^m \}$ and $\mathcal{S}_2 := \{ \xi \in \mathbb{R}^{\ell} : \xi = (\otimes_{i=m}^1 \rho_i^{[k_i]} \otimes I_n)x, \xi \neq 0, \text{ some } \rho \in \mathbb{R}^m, \text{ and } x \in \mathbb{R}^n \}$. Then $\mathcal{S}_1 = \mathcal{S}_2$. \square

Proof: Assume that $\xi \in \mathcal{S}_2$. Then there exists $\rho \in \mathbb{R}^m$ and $x \in \mathbb{R}^n$ such that $\xi = (\rho_m^{[k_m]} \otimes \dots \otimes \rho_1^{[k_1]} \otimes I_n)x$. Use this particular ρ and construct the matrices \mathcal{J}_K , \mathcal{C}_K and $\Delta_K(\rho)$. It can be easily verified that $(\mathcal{J}_K - \Delta_K(\rho)\mathcal{C}_K)(\rho_m^{[k_m]} \otimes \dots \otimes \rho_1^{[k_1]} \otimes I_n) = 0$. It follows that $\xi \in \mathcal{S}_1$. Hence $\mathcal{S}_2 \subseteq \mathcal{S}_1$.

Assume now that $\xi \in \mathcal{S}_1$ and $\xi \neq 0$. Rewrite $\xi \in \mathbb{R}^{k_m \dots k_1 n}$ in the form $\xi = \xi_m \otimes \xi_{m-1} \otimes \dots \otimes \xi_1 \otimes x$ where $\xi_i \in \mathbb{R}^{k_i}$ and $x \in \mathbb{R}^n$. It is easy to show that such vectors $\xi_1, \xi_2, \dots, \xi_m$ and x always exist. From hypothesis, we have that

$$(\mathcal{J}_K - \Delta_K(\rho)\mathcal{C}_K)(\xi_m \otimes \xi_{m-1} \otimes \dots \otimes \xi_1 \otimes x) = 0, \quad \rho \in \mathbb{R}^m \quad (17)$$

The previous equation implies, in particular, that

$$\begin{aligned} & \left(\check{J}_m \otimes \check{J}_{m-1} \otimes \dots \otimes \check{J}_2 \otimes (\check{J}_{k_1-1} - \rho_1 \hat{J}_{k_1-1}) \otimes I_n \right) \cdot \\ & (\xi_m \otimes \xi_{m-1} \otimes \dots \otimes \xi_2 \otimes (\xi_1 \otimes x)) = 0, \end{aligned}$$

or that

$$\begin{aligned} & \left((\check{J}_m \otimes \dots \otimes \check{J}_2)(\xi_m \otimes \dots \otimes \xi_2) \right) \otimes \\ & \left((\check{J}_{k_1-1} - \rho_1 \hat{J}_{k_1-1})\xi_1 \right) \otimes (I_n \otimes x) = 0. \end{aligned} \quad (18)$$

Assume now that $(\check{J}_m \otimes \dots \otimes \check{J}_2)(\xi_m \otimes \dots \otimes \xi_2) = \otimes_{i=m}^2 \check{J}_i \xi_i = 0$. If $\check{J}_j \xi_j = 0$ for some $j \in \{2, \dots, m\}$ then $\hat{J}_{k-j} \xi_j = \check{J}_{k-j} \xi_j = 0$. It follows that $\xi_j = 0$ and thus $\xi = 0$, leading to a contradiction. Similarly, if $I_n \otimes x = 0$ we have that $x = 0$ and hence $\xi = 0$, also a contradiction. Therefore, from (18) we have necessarily, $(\check{J}_{k_1-1} - \rho_1 \hat{J}_{k_1-1})\xi_1 = 0$. Using now Lemma 4.3 of [15] the last equation implies that $\xi_1 = \rho_1^{[k_1]} \otimes x$ for some $\rho_1 \in \mathbb{R}$. Therefore, $\xi = \xi_m \otimes \dots \otimes \xi_2 \otimes \rho_1^{[k_1]} \otimes x$. Repeating this process, one can show that (17) also implies that

$$\begin{aligned} & \left(\check{J}_m \otimes \dots \otimes \check{J}_3 \otimes (\check{J}_{k_2-1} - \rho_2 \hat{J}_{k_2-1}) \otimes \check{J}_1 \otimes I_n \right) \cdot \\ & \left(\xi_m \otimes \dots \otimes \xi_2 \otimes \rho_1^{[k_1]} \otimes x \right) = 0, \end{aligned}$$

or that,

$$\begin{aligned} & \left((\check{J}_m \otimes \dots \otimes \check{J}_3)(\xi_m \otimes \dots \otimes \xi_3) \right) \otimes \\ & \left((\check{J}_{k_2-1} - \rho_2 \hat{J}_{k_2-1})\xi_2 \right) \otimes \left((\check{J}_1 \otimes I_n)(\rho_1^{[k_1]} \otimes x) \right) = 0, \end{aligned} \quad (19)$$

from which we have that, necessarily, $(\check{J}_{k_2-1} - \rho_2 \hat{J}_{k_2-1})\xi_2 = 0$, implying that $\xi_2 = \rho_2^{[k_2]}$. It follows that ξ can be written as

$\xi = \xi_m \otimes \dots \otimes \rho_2^{[k_2]} \otimes \rho_1^{[k_1]} \otimes x$. Repeating this process, one obtains that ξ can be written as $\xi = \rho_m^{[k_m]} \otimes \dots \otimes \rho_1^{[k_1]} \otimes x = (\otimes_{i=1}^m \rho_i^{[k_i]} \otimes I_n)x$, for some $\rho_i \in \mathbb{R}$ ($i = 1, \dots, m$) and $x \in \mathbb{R}^n$. Therefore $\xi \in \mathcal{S}_2$ and thus $\mathcal{S}_1 \subseteq \mathcal{S}_2$. This completes the proof that $\mathcal{S}_1 = \mathcal{S}_2$. ■

Returning now to Theorem 3.1, recall that the condition $P(\rho) > 0$ is equivalent to the fact that for any $x \in \mathbb{R}^n$, $x^\top P(\rho)x > 0$, which via (13) can be written as

$$x^\top (\otimes_{i=1}^m \rho_i^{[\bar{\alpha}_i]} \otimes I_n)^\top P_\Sigma (\otimes_{i=1}^m \rho_i^{[\bar{\alpha}_i]} \otimes I_n)x > 0.$$

Let $\xi = (\rho_m^{[\bar{\alpha}_m]} \otimes \dots \otimes \rho_1^{[\bar{\alpha}_1]} \otimes I_n)x$. Using Lemma 4.3 the condition $P(\rho) > 0$ is equivalent to the condition

$$\xi^\top P_\Sigma \xi > 0 \text{ such that } (\mathcal{J}_K - \Delta_K(\rho)\mathcal{C}_K)\xi = 0, \quad \forall \xi \neq 0.$$

For the following result we assume that Ω is a compact and connected subset of \mathbb{R}^m . Without loss of generality we take $\Omega = [-1, +1]^m$.

Theorem 4.1: Assume that there exist positive definite matrices $D_1, D_2, \dots, D_m \in \mathbb{R}^{q_2^{2^{m-1}} \times q_2^{2^{m-1}}}$ where $q = n(\bar{\alpha}_1 - 1)(\bar{\alpha}_2 - 1) \dots (\bar{\alpha}_m - 1)$ and skew-symmetric matrices $G_1, G_2, \dots, G_m \in \mathbb{R}^{q_2^{2^{m-1}} \times q_2^{2^{m-1}}}$ such that

$$-P_\Sigma + \begin{bmatrix} \mathcal{J}_K \\ \mathcal{C}_K \end{bmatrix}^\top \begin{bmatrix} -D & G \\ G^\top & D \end{bmatrix} \begin{bmatrix} \mathcal{J}_K \\ \mathcal{C}_K \end{bmatrix} < 0, \quad (20)$$

where $D := \text{diag}[D_1, \dots, D_m]$, $G := \text{diag}[G_1, \dots, G_m]$, \mathcal{J}_K and \mathcal{C}_K as before, with $K = (\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_m)$. Then

$$(\otimes_{i=1}^m \rho_i^{[\bar{\alpha}_i]} \otimes I_n)^\top P_\Sigma (\otimes_{i=1}^m \rho_i^{[\bar{\alpha}_i]} \otimes I_n) > 0$$

for all $\rho = (\rho_1, \rho_2, \dots, \rho_m)^\top \in [-1, +1]^m$. □

Proof: The matrix inequality $P(\rho) > 0$ for all $\rho \in [-1, +1]^m$ is equivalent to the scalar inequality $x^\top P(\rho)x > 0$ for all $x \in \mathbb{R}^n$ and for all $\rho \in [-1, +1]^m$. Let $\xi = (\otimes_{i=1}^m \rho_i^{[\bar{\alpha}_i]} \otimes I_n)x$. It follows from Lemma 4.3 that $(\mathcal{J}_K - \Delta_K(\rho)\mathcal{C}_K)\xi = 0$, where \mathcal{J}_K , $\Delta_K(\rho)$ and \mathcal{C}_K as before. Therefore, the condition $P(\rho) > 0$ for all $\rho \in [-1, +1]^m$ is equivalent to the condition

$$\xi^\top P_\Sigma \xi > 0, \text{ such that } [I, -\Delta_K(\rho)] \begin{bmatrix} \mathcal{J}_K \\ \mathcal{C}_K \end{bmatrix} \xi = 0, \quad \forall \xi \neq 0. \quad (21)$$

and for all $\rho \in [-1, +1]^m$. According to Lemma 4.2, inequality (21) is equivalent to the existence of a matrix $\Theta = \Theta^\top$, such that

$$-P_\Sigma + \begin{bmatrix} \mathcal{J}_K \\ \mathcal{C}_K \end{bmatrix}^\top \Theta \begin{bmatrix} \mathcal{J}_K \\ \mathcal{C}_K \end{bmatrix} < 0, \quad (22)$$

and

$$\begin{bmatrix} \Delta_K(\rho) \\ I \end{bmatrix}^\top \Theta \begin{bmatrix} \Delta_K(\rho) \\ I \end{bmatrix} \geq 0, \quad \forall \rho \in [-1, +1]^m. \quad (23)$$

Now, the condition $\rho_i \in [-1, +1]$ for all $i = 1, 2, \dots, m$ is equivalent to the existence of positive definite matrices $D_1, D_2, \dots, D_m \in \mathbb{R}^{q_2^{2^{m-1}} \times q_2^{2^{m-1}}}$ and skew-symmetric matrices $G_1, G_2, \dots, G_m \in \mathbb{R}^{q_2^{2^{m-1}} \times q_2^{2^{m-1}}}$ such that

$$\text{block-diag}[(1 - \rho_i^2)D_i] + \text{block-diag}[\rho_i(G_i + G_i^\top)] \geq 0,$$

Equivalently,

$$\begin{bmatrix} \Delta_K(\rho) \\ I \end{bmatrix}^\top \begin{bmatrix} -D & G \\ G^\top & D \end{bmatrix} \begin{bmatrix} \Delta_K(\rho) \\ I \end{bmatrix} \geq 0, \quad (24)$$

where $D = \text{diag}[D_1, \dots, D_m]$ and $G = \text{diag}[G_1, \dots, G_m]$.

In summary, the condition $P(\rho) > 0$ is equivalent to the feasibility of the inequalities (22) and (23), the latter being implied by the feasibility of inequality (24). ■

Using the previous result we are now ready to use the main result from Theorem 3.1 to cast the stability question of (1) over the domain $\Omega = [-1, +1]^m$ as a convex feasibility problem in terms of LMIs.

Theorem 4.2: Let $A_i \in \mathbb{R}^{n \times n}$, ($i = 0, 1, 2, \dots, m$) and $\rho = (\rho_1, \rho_2, \dots, \rho_m)^\top \in [-1, +1]^m$ and assume that $\dim \mathcal{N}(A_i) = r_i$. Let $\bar{k}_i = \min\{\frac{1}{2}n(n+1) - 1, \frac{1}{2}(n-r_i)(n+r_i+1)\}$, $\bar{\alpha}_i = \lceil \frac{\bar{k}_i}{2} \rceil + 1$, $q_1 = n \prod_{i=1}^m (\bar{\alpha}_i - 1)$, $q_2 = n \prod_{i=1}^m \bar{\alpha}_i$, $K_1 = (\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_m)^\top$ and $K_2 = ((\bar{\alpha}_1 + 1), (\bar{\alpha}_2 + 1), \dots, (\bar{\alpha}_m + 1))^\top$. Assume that there exist symmetric matrix $P_\Sigma \in \mathbb{R}^{q_2 \times q_2}$, positive definite matrices $D_1, D_2, \dots, D_m \in \mathbb{R}^{q_1 2^{m-1} \times q_1 2^{m-1}}$, skew-symmetric matrices $G_1, G_2, \dots, G_m \in \mathbb{R}^{q_1 2^{m-1} \times q_1 2^{m-1}}$, positive definite matrices $E_1, E_2, \dots, E_m \in \mathbb{R}^{q_2 2^{m-1} \times q_2 2^{m-1}}$ and skew-symmetric matrices $\Gamma_1, \Gamma_2, \dots, \Gamma_m \in \mathbb{R}^{q_2 2^{m-1} \times q_2 2^{m-1}}$ such that

$$-P_\Sigma + \begin{bmatrix} \mathcal{J}_{K_1} \\ \mathcal{C}_{K_1} \end{bmatrix}^\top \begin{bmatrix} -D & G \\ G^\top & D \end{bmatrix} \begin{bmatrix} \mathcal{J}_{K_1} \\ \mathcal{C}_{K_1} \end{bmatrix} < 0,$$

$$H_\Sigma^\top P_\Sigma F_\Sigma + F_\Sigma^\top P_\Sigma H_\Sigma + \begin{bmatrix} \mathcal{J}_{K_2} \\ \mathcal{C}_{K_2} \end{bmatrix}^\top \begin{bmatrix} -E & \Gamma \\ \Gamma^\top & E \end{bmatrix} \begin{bmatrix} \mathcal{J}_{K_2} \\ \mathcal{C}_{K_2} \end{bmatrix} < 0,$$

where, $H_\Sigma = \hat{J}_{\bar{\alpha}_m} \otimes \dots \otimes \hat{J}_{\bar{\alpha}_1} \otimes I_n$, $F_\Sigma = \hat{J}_{\bar{\alpha}_m} \otimes \dots \otimes \hat{J}_{\bar{\alpha}_1} \otimes A_0 + \sum_{i=1}^m \hat{J}_{\bar{\alpha}_m} \otimes \dots \otimes \hat{J}_{\bar{\alpha}_{i+1}} \otimes \hat{J}_{\bar{\alpha}_i} \otimes \hat{J}_{\bar{\alpha}_{i-1}} \otimes \dots \otimes \hat{J}_{\bar{\alpha}_1} \otimes A_i$, and where $D = \text{diag}[D_1, \dots, D_m]$, $G = \text{diag}[G_1, \dots, G_m]$, $E = \text{diag}[E_1, \dots, E_m]$ and $\Gamma = \text{diag}[\Gamma_1, \dots, \Gamma_m]$. Then the matrix $A(\rho) = \sum_{i=0}^m \rho_i A_i$ is Hurwitz for all $\rho \in [-1, +1]^m$. □

V. NUMERICAL EXAMPLE

A numerical example is given below to demonstrate the application of Theorem 4.2.

Example 2: Consider the two-parameter dependent matrix $A(\rho) = A_0 + \rho_1 A_1 + \rho_2 A_2$ where

$$A_0 = \begin{bmatrix} -2 & 7 \\ 0 & -1 \end{bmatrix}, \quad A_1 = \begin{bmatrix} \frac{1}{2} & 3 \\ 0 & -\frac{1}{3} \end{bmatrix}, \quad A_2 = \begin{bmatrix} 1 & -4 \\ 0 & \frac{1}{2} \end{bmatrix}$$

The eigenvalues of $A(\rho)$ are given by $\lambda_1 = -2 + \frac{1}{2}\rho_1 + \rho_2$ and $\lambda_2 = -1 - \frac{1}{3}\rho_1 + \frac{1}{2}\rho_2$. Therefore, $A(\rho)$ is Hurwitz for all $(\rho_1, \rho_2) \in [-1, +1]^2$. For this problem $n = 2$, $m = 2$, $\bar{k}_1 = \bar{k}_2 = \bar{k} = \frac{1}{2}n(n+1) - 1 = 2$, $\bar{\alpha}_1 = \bar{\alpha}_2 = \bar{\alpha} = \lceil \frac{\bar{k}}{2} \rceil + 1 = 2$. Moreover, $q_1 = (\bar{\alpha} - 1)^m n = 2$ and $q_2 = \bar{\alpha}^m n = 8$. Thus, $K_1 = (\bar{\alpha}, \bar{\alpha})^\top = (2, 2)^\top$, $K_2 = ((\bar{\alpha} + 1), (\bar{\alpha} + 1))^\top = (3, 3)^\top$. Hence, $P_\Sigma \in \mathbb{R}^{8 \times 8}$, $D_1, D_2 \in \mathbb{R}^{4 \times 4}$ and $E_1, E_2 \in \mathbb{R}^{16 \times 16}$. The matrices $\mathcal{C}_{K_1}, \mathcal{C}_{K_2}, \mathcal{J}_{K_1}$ and \mathcal{J}_{K_2} are given by

$$\mathcal{C}_{K_1} = \begin{bmatrix} \hat{J}_1 \otimes \hat{J}_1 \otimes I_2 \\ \hat{J}_1 \otimes \hat{J}_1 \otimes I_2 \\ \hat{J}_1 \otimes \hat{J}_1 \otimes I_2 \\ \hat{J}_1 \otimes \hat{J}_1 \otimes I_2 \end{bmatrix}, \quad \mathcal{J}_{K_1} = \begin{bmatrix} \hat{J}_1 \otimes \check{J}_1 \otimes I_2 \\ \check{J}_1 \otimes \hat{J}_1 \otimes I_2 \\ \hat{J}_1 \otimes \check{J}_1 \otimes I_2 \\ \check{J}_1 \otimes \hat{J}_1 \otimes I_2 \end{bmatrix},$$

$$\mathcal{C}_{K_2} = \begin{bmatrix} \hat{J}_2 \otimes \hat{J}_2 \otimes I_2 \\ \hat{J}_2 \otimes \hat{J}_2 \otimes I_2 \\ \hat{J}_2 \otimes \hat{J}_2 \otimes I_2 \\ \hat{J}_2 \otimes \hat{J}_2 \otimes I_2 \end{bmatrix}, \quad \mathcal{J}_{K_2} = \begin{bmatrix} \hat{J}_2 \otimes \check{J}_2 \otimes I_2 \\ \check{J}_2 \otimes \hat{J}_2 \otimes I_2 \\ \hat{J}_2 \otimes \check{J}_2 \otimes I_2 \\ \check{J}_2 \otimes \hat{J}_2 \otimes I_2 \end{bmatrix},$$

and H_Σ and F_Σ are given by $H_\Sigma = \hat{J}_2 \otimes \hat{J}_2 \otimes I_2$ and $F_\Sigma = \hat{J}_2 \otimes \hat{J}_2 \otimes A_0 + \hat{J}_2 \otimes \check{J}_2 \otimes A_1 + \check{J}_2 \otimes \hat{J}_2 \otimes A_2$.

$$P_{\Sigma} = \begin{bmatrix} 27.9276 & 51.0744 & -0.7887 & 16.8161 & -1.4679 & -20.1029 & -1.2207 & 1.5418 \\ 51.0744 & 486.7451 & 13.0354 & 101.0287 & 8.6774 & 8.6872 & 9.1953 & 52.8509 \\ -0.7887 & 13.0354 & 9.1765 & 17.2759 & 0.8705 & -0.8746 & 1.4118 & -4.9874 \\ 16.8161 & 101.0287 & 17.2759 & 244.3918 & 4.3396 & -39.0897 & 6.6145 & 46.1743 \\ -1.4679 & 8.6774 & 0.8705 & 4.3396 & 8.7297 & 8.4651 & -0.8661 & 4.9237 \\ -20.1029 & 8.6872 & -0.8746 & -39.0897 & 8.4651 & 239.4326 & 5.1983 & 13.5890 \\ -1.2207 & 9.1953 & 1.4118 & 6.6145 & -0.8661 & 5.1983 & -0.9111 & -0.3332 \\ 1.5418 & 52.8509 & -4.9874 & 46.1743 & 4.9237 & 13.5890 & -0.3332 & 25.5901 \end{bmatrix}$$

Solving the LMIs of Theorem 4.2 one obtains a possible solution for P_{Σ} (see next page) and D_1, D_2 as follows

$$D_1 = \begin{bmatrix} 9.5250 & 6.9870 & -1.0628 & -2.8941 \\ 6.9870 & 65.6791 & 0.0831 & -3.5221 \\ -1.0628 & 0.0831 & 9.9204 & 3.9213 \\ -2.8941 & -3.5221 & 3.9213 & 69.1830 \end{bmatrix},$$

$$D_2 = \begin{bmatrix} 9.4393 & 9.0572 & -1.0995 & 1.3359 \\ 9.0572 & 69.1088 & 2.2309 & 2.5806 \\ -1.0995 & 2.2309 & 9.7363 & 6.1760 \\ 1.3359 & 2.5806 & 6.1760 & 71.0502 \end{bmatrix}.$$

and $G_1 = G_2 = 0$. Due to space limitations the numerical values of E_1, E_2, Γ_1 and Γ_2 are omitted. Using the results of Theorem 4.2 we conclude that $A(\rho)$ is Hurwitz for all $\rho \in [-1, +1]^2$. The solution was obtained using the LMI Toolbox from MATLAB [24]. The solution was obtained after about 1 sec on a computer with a 3.2GHz Pentium processor.

VI. CONCLUSIONS

In this paper we generalize the results of [15] to multi-parameter LTI systems. Specifically, we show that the stability of a multi-parameter, affinely-dependent LTI systems of the form $\dot{x}(t) = A(\rho)x(t)$ is equivalent to the existence of a polynomial, parameter-dependent Lyapunov matrix $P(\rho)$ of a known degree satisfying the matrix inequalities $P(\rho) > 0$ and $A(\rho)P(\rho) + P(\rho)A^T(\rho) < 0$. We also show that testing these two inequalities over a compact, connected set can be cast into a finite-dimensional convex feasibility problem in terms of LMIs. Of course, the dimension of the resulting LMIs is still high (recall that the problem is NP-hard).

Acknowledgment: This work was supported in part by NSF award no. CMS-9996120 and AFOSR award no. F49620-00-1-0374.

REFERENCES

- [1] M. Rotea, M. Corless, D. Da, and I. Petersen, "Systems with structured uncertainty: Relations between quadratic and robust stability," *IEEE Transactions on Automatic Control*, vol. 38, no. 5, pp. 799–803, 1993.
- [2] A. Helmerrson, "Parameter dependent Lyapunov functions based on Linear Fractional Transformation," in *14th World Congress of IFAC*, vol. F. Beijing, China: IFAC, July 1999, pp. 537–542.
- [3] D. S. Bernstein and W. M. Haddad, "Robust stability and performance analysis for state space system via quadratic Lyapunov bounds," *SIAM Journal of Matrix Analysis and Application*, vol. 11, pp. 239–271, 1990.
- [4] W. M. Haddad and D. S. Bernstein, "Parameter-dependent Lyapunov functions and the Popov criterion in robust analysis and synthesis," *IEEE Transactions on Automatic Control*, vol. 40, pp. 536–543, 1995.
- [5] T. Iwasaki and G. Shibata, "LPV system analysis via quadratic separator for uncertain implicit systems," *IEEE Transactions on Automatic Control*, vol. 46, no. 8, pp. 1195–1208, 2001.
- [6] P. Apkarian, "Advanced gain-scheduling techniques for uncertain systems," *IEEE Transactions on Control Systems Technology*, vol. 6, pp. 21–32, 1998.
- [7] K. S. Narendra and J. H. Taylor, *Frequency Domain Criteria for Absolute Stability*. New York, NY: Academic Press, 1973.
- [8] S. Dasgupta, B. D. O. Anderson, and M. Fu, "Lyapunov functions for uncertain systems with applications to the stability of time varying systems," *IEEE Transactions on Circuits and Systems*, vol. 41, no. 2, pp. 93–106, 1994.
- [9] V. Blondel and J. N. Tsitsiklis, "NP-hardness of some linear control design problems," in *Proceedings of the IEEE 34th Conference on Decision and Control*, Dec. 1995, pp. 2910–2915, New Orleans, LA.
- [10] D. Peaucelle and D. Arzelier, "Robust performance analysis with LMI-based methods for real parametric uncertainty via parameter-dependent Lyapunov functions," *IEEE Transactions on Automatic Control*, vol. 46, no. 4, pp. 624–630, April 2001.
- [11] P.-A. Bliman, "Nonconservative LMI approach to robust stability for systems with uncertain scalar parameters," in *Proceedings of the IEEE 41st Conference on Decision and Control*, Dec. 2002, pp. 305–310, Las Vegas, NV.
- [12] —, "An existence result for polynomial solutions of parameter-dependent LMIs," *Systems & Control Letters*, vol. 51, no. 3–4, pp. 165–169, 2004.
- [13] —, "A convex approach to robust stability for linear systems with uncertain scalar parameters," *SIAM Journal on Control and Optimization*, vol. 42, no. 6, pp. 2016–2042, 2004.
- [14] X. Zhang, "Parameter-dependent Lyapunov functions and stability analysis of linear parameter-dependent dynamical systems," Ph.D. dissertation, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, October 2003.
- [15] X. Zhang, P. Tsiotras, and T. Iwasaki, "Parameter-dependent Lyapunov functions for stability analysis of LTI parameter dependent systems," in *Proceedings of the IEEE 42nd Conference on Decision and Control*, 2003, pp. 5168–5173, Maui, HI.
- [16] G. Chesi, "Robust analysis of linear systems affected by time-invariant hypercubic parameter uncertainty," in *Proceedings of the 42nd IEEE Conference on Decision and Control*, 2003, pp. 5019–5024, Maui, HI.
- [17] R. A. Horn and C. R. Johnson, *Matrix Analysis*. Cambridge, United Kingdom: Cambridge University Press, 1991.
- [18] J. W. Brewer, "Kronecker products and matrix calculus in system theory," *IEEE Transactions on Circuits and Systems*, vol. 25, pp. 772–781, 1978.
- [19] D. Mustafa, "Block Lyapunov sum with applications to integral controllability and maximal stability of singularly perturbed systems," *International Journal of Control*, vol. 61, pp. 47–63, 1995.
- [20] J. R. Magnus, *Linear Structures*. London: Charles Griffin, 1988.
- [21] K. Zhou, J. C. Doyle, and K. Glover, *Robust and Optimal Control*. Prentice-Hall, 1996.
- [22] S. Rern, P. T. Kabamba, and D. S. Bernstein, "Guardian map approach to robust stability of linear systems with constant real parameter uncertainty," *IEEE Transactions on Automatic Control*, vol. 39, pp. 162–164, 1994.
- [23] X. Zhang, A. Lanzon, and P. Tsiotras, "On robust stability of LTI parameter dependent systems," in *10th Mediterranean Conference on Control and Automation*, July 2002, Lisbon, Portugal.
- [24] P. Gahinet, A. Nemirovski, A. J. Laub, and M. Chilali, *LMI Control Toolbox, For Use with MATLAB*. Natick, MA: The Math Works Inc., 2000.