Appendix A

Linear Matrix Inequalities (LMIs)

Definition A.1 *A Linear Matrix Inequality (LMI) [3] is a constraint of the form*

$$G(x) := G_0 + \sum_{j=1}^{n} x_j G_j < 0, \tag{A.1}$$

where $x = [x_1,\ x_2, \cdots, x_n]^T \in \mathbb{R}^n$ *is the unknown vector of optimization variables.* $G_j = G_j^T \in \mathbb{R}^{m \times m}$ *are known symmetric matrices.*

The Lyapunov inequality can be expressed in the form of LMIs as:

$$A^T X + X A^T < 0, X > 0, \quad \text{For continuous-time systems} \tag{A.2}$$

$$A^T X A - X < 0, X > 0, \quad \text{For discrete-time systems} \tag{A.3}$$

For example, consider the inequalities as:

$$y > 0,\ y - x^2 > 0 \tag{A.4}$$

In LMI Form, (A.4) can be written as $\begin{bmatrix} y & x \\ x & 1 \end{bmatrix} > 0$, and in standard form, it is written as

$$\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} + y \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} + x \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} > 0 \tag{A.5}$$

where x, y are decision variables.

The following are some of the properties of LMIs:

- The LMI (A.1) is a convex constraint on x, which implies that its solution set (feasibility set) $\mathcal{S} \subset \mathbb{R}^n$ and the problem thereby formed is a convex optimization problem. Such LMIs are advantageous in the sense that these constraints can be solved using numerical techniques even if analytical solutions are, in general, not possible.

- LMIs are non unique. The same set of variable x can be represented as the feasibility set of different LMIs. For instance, consider the following:

$$A > 0 \Leftrightarrow x^T A x > 0,\ \forall x \neq 0,$$
$$\Leftrightarrow y^T T^T A T y > 0,\ \forall y \neq 0, \det T \neq 0, \Leftrightarrow T^T A T > 0.$$

  Similarly, rearrangements do not affect the feasibility set, for instance,

$$\begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} > 0 \Leftrightarrow \begin{bmatrix} 0 & I \\ I & 0 \end{bmatrix} \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} \begin{bmatrix} 0 & I \\ I & 0 \end{bmatrix} > 0 \Leftrightarrow \begin{bmatrix} A_4 & A_3 \\ A_2 & A_1 \end{bmatrix} > 0$$

- Multiple LMIs can be considered equivalent to a single LMI, for instance, consider a set of m LMIs: $G^1(x) > 0; \cdots, G^m(x) > 0$. Then, the single equivalent LMI is given by $G(x) = Diag\{G^1(x), \cdots, G^m(x)\} > 0$.

- The solutions obtained through LMI is a global solution.

A.1 Solving LMIs

Several packages available for solving LMI problems. Once an LMI problem is specified, it can be solved numerically by calling LMI solvers. There are three types of problems which can be solved using LMI solver. For a comprehensive guide on the LMI solver softwares, and the algorithms behind them, the reader is directed to refer to [187]. The software used in this work for solving LMI problems is the LMI CONTROL TOOLBOX in MATLAB [158]. Three LMI solvers commonly used are feasp, mincx,and gevp to solve the following problems.

A.2 LMI problem forms

A.2.1 Feasibility problem

A feasibility problem is defined as: Find a solution

$$x = (x_1, x_2, \cdots, x_n) \text{ such that } F(x) > 0 \tag{A.6}$$

- LMI solver : feasp
- Syntax: [tmin, xfeas]=feasp(lmisys,options,target)

A.2.2 Linear objective minimization problem

The minimization problem is defined as:

$$\text{Minimize } c^T x, \text{ subject to } F(x) > 0 \tag{A.7}$$

where $x = (x_1, x_2, \cdots, x_n)$ and $c \in \mathcal{R}^n$ is a given vector.

- LMI solver : mincx
- Syntax: [copt, xopt]=mincx(lmisys,options,xinit,target)

A.2.3 Generalized eigenvalue minimization problem

This eigen value minimization problem can be stated as:

$$\text{Minimize } \lambda, \text{ subject to } A(x) < \lambda B(x),\ B(x) > 0,\ C(x) < D(x) \tag{A.8}$$

where $x = (x_1, x_2, \cdots, x_n)$ and λ is an eigen value.

- LMI solver : gevp
- Syntax: [λ opt, xopt]=gevp(lmisys,options,xinit,target)

A.3 Schur Complement

It plays as an important tool in carrying out the synthesis of the SOF controller design. The basic idea of using Schur complements is to convert nonlinear inequality constraints into linear constraints on symmetric matrices. It is defined as :

Definition A.2 *[3] Let $Q(x)$, $R(x)$ and $S(x)$ are affine functions in x. Then,*

$$\begin{bmatrix} Q(x) & S(x) \\ S^T(x) & R(x) \end{bmatrix} > 0 \Leftrightarrow Q(x) > 0, R(x) - S^T(x)Q^{-1}(x)S(x) > 0 \tag{A.9}$$

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List of Publications

Journals

- **J. K. Goyal** , S. Aggarwal , S. Ghosh, S. Kamal and P. Dworak, 2021. *L_2 based Static Output Feedback Controller Design for a Class of Polytopic Systems with Actuator Saturation. International Journal of Control* (Accepted).
- **J. K. Goyal**, S. Aggarwal, S. Ghosh, S. Kamal, and P. Dworak, 2020. *Quasi-LPV PI Control of TRMS subject to Actuator Saturation. IET Control Theory & Applications, DOI:10.1049/iet-cta.2020.0361.*
- **J. K. Goyal**, S. Ghosh, and S. Kamal, 2019. *New LMI conditions for H_∞/H_2 output feedback control of linear discrete-time systems. International Journal of Control, DOI:https://doi.org/10.1080/00207179.2019.1665712.*
- **J. K. Goyal** , S. Aggarwal , S. Ghosh, S. Kamal. *Output Feedback Pole-Placement in Damping Region for Discrete-Time Uncertain Systems. European Journal of Control* (Under review).
- **J. K. Goyal** , P.R. Sahoo, S. Aggarwal , S. Ghosh, S. Kamal. *An improved output feedback controller design for linear discrete-time systems using a matrix decomposition method. Journal of Dynamic Systems, Measurement, and Control* (Under review).
- P.R. Sahoo, **J. K. Goyal**, S. Ghosh and A.K. Naskar, 2019. *New results on restricted static output feedback H_∞ controller design with regional pole placement. IET Control Theory & Applications, 13(8), pp.1095-1104.*
- **J. K. Goyal**, S. Kamal, R.B. Patel, X. Yu, J.P. Mishra and S. Ghosh, 2019. *Higher Order Sliding Mode Control Based Finite-time Constrained Stabilization. IEEE Transactions on Circuits and Systems II: Express Briefs, DOI:https://doi.org/10.1109/TCSII.2019.2903495.*
- P. Dworak, **J. K. Goyal**, S. Aggarwal and S. Ghosh *Effective Use of MPC for Dynamic Decoupling of MIMO Systems. Elektronika ir Elektrotechnika 25, no. 2*

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- S. Kamal, P. R. Kumar, A. Chalanga, **J. K. Goyal**, B. Bandyopadhyay and L. Fridman, 2020. *A New Class of Uniform Continuous Higher-Order Sliding Mode Controllers. Journal of Dynamic Systems, Measurement, and Control, 142(1), DOI: https://doi.org/10.1115/1.4044952.*

- S. Aggarwal, **J. K. Goyal**, S. Ghosh, S. Kamal and P. Dworak, 2020. *New Decentralised Event-Triggered Consensus Strategy for Single and Double Integrator Multi-Agent Systems*, *IEEE Access, DOI:10.1109/ACCESS.2020.3017012.*

Conferences

- **J. K. Goyal**, S. Aggarwal, S. Ghosh, and S. Kamal, 2019. *H_∞ based PI Controller Design for Coupled Tank System through Polytopic Modeling. In 2019 IEEE IECON, 45th Annual Conference of the Industrial Electronics Society*, Portugal.

- **J. K. Goyal**, S. Aggarwal, S. Ghosh, and S. Kamal, 2019. *Robust H_∞ Based PI Control Design For 2-DOF Helicopter: An LMI Approach. In 2019 IEEE International Conference on Range Technology (ICORT)*, Chandipur, Odisha, India.

- **J. K. Goyal**, S. Aggarwal, S. Ghosh, S. Kamal and Dworak, Pawel, 2020. *Experimental Design of Robust Decentralized PI controller for TRMS through Polytopic Modeling. In 2020, IEEE 21st International Conference on Industrial Technology*, Buenos Aires, Argentina.

- **J. K. Goyal**, S. Aggarwal, S. Ghosh, and S. Kamal, 2020. *Design of Robust PID Controller using Static Output Feedback framework. In ACODS 2020 in association with IFAC, 6th International Conference On Advances in Control & Optimization of Dynamical Systems*, IIT Madras, Chennai, India.

- A.K. Pal , B. Singh, S. Kamal , S.K. Nagar, **J. K. Goyal**, 2020. *Arbitrary Time Stabilization of a Coupled Tank System: A Contraction based Approach. In 2020, IEEE 21st International Conference on Industrial Technology*, Buenos Aires, Argentina.

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