

Semidefinite Programming, Computational Intelligence, Lecture 10

by Sergei Savin

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SEMIDEFINITE PROGRAMMING (SDP)

General form

General form of a semidefinite program is:

$$\begin{array}{ll} \underset{\mathbf{x}}{\text{minimize}} & \mathbf{c}^\top \mathbf{x}, \\ \text{subject to} & \begin{cases} \mathbf{G} + \sum \mathbf{F}_i x_i \preceq 0, \\ \mathbf{A}\mathbf{x} = \mathbf{b}. \end{cases} \end{array} \quad (1)$$

where $\mathbf{F}_i \succeq 0$ and $\mathbf{G} \succeq 0$ (meaning they are positive semidefinite).

Constraint $\mathbf{G} + \sum \mathbf{F}_i x_i \preceq 0$ is called *linear matrix inequality* or *LMI*.

SEMIDEFINITE PROGRAMMING (SDP)

Multiple LMI

SDP can have several LMIs. Assume you have:

$$\begin{cases} \mathbf{G} + \sum \mathbf{F}_i x_i \preceq 0 \\ \mathbf{D} + \sum \mathbf{H}_i x_i \preceq 0 \end{cases} \quad (2)$$

This is equivalent to:

$$\begin{bmatrix} \mathbf{G} & \mathbf{0} \\ \mathbf{0} & \mathbf{D} \end{bmatrix} + \sum \begin{bmatrix} \mathbf{F}_i & \mathbf{0} \\ \mathbf{0} & \mathbf{H}_i \end{bmatrix} x_i \preceq 0 \quad (3)$$

SEMIDEFINITE PROGRAMMING (SDP)

SDP decision variable

Sometimes it is easier to directly think of semidefinite matrices as of decision variables. This leads to programs with such formulation:

$$\begin{array}{ll} \underset{\mathbf{X}}{\text{minimize}} & f(\mathbf{X}), \\ \text{subject to} & \begin{cases} \mathbf{X} \preceq 0, \\ \mathbf{g}(\mathbf{X}) = \mathbf{0}. \end{cases} \end{array} \quad (4)$$

where cost and constraints should adhere to SDP limitations.

Ex. 1: CONTINUOUS LYAPUNOV EQ. AS SDP/LMI

Mathematical formulation

In control theory, Lyapunov equation is a condition of whether or not a continuous LTI system $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x}$ is stabilizable:

$$\begin{cases} \mathbf{A}^\top \mathbf{P} + \mathbf{P}\mathbf{A} + \mathbf{Q} = 0 \\ \mathbf{P} \succeq 0 \\ \mathbf{Q} \succeq 0 \end{cases} \quad (5)$$

where decision variable is \mathbf{P} . This can be represented as an SDP:

$$\begin{aligned} & \underset{\mathbf{P}}{\text{minimize}} && 0, \\ & \text{subject to} && \begin{cases} \mathbf{P} \succeq 0, \\ \mathbf{A}^\top \mathbf{P} + \mathbf{P}\mathbf{A} + \mathbf{Q} = 0. \end{cases} \end{aligned} \quad (6)$$

Ex. 1: CONTINUOUS LYAPUNOV EQ. AS SDP/LMI

Code

```
0 n = 7; A = randn(n, n) - 3*rand*eye(n);
  Q = eye(n);
2
  cvx_begin sdp
4      variable P(n, n) symmetric
      minimize 0
6      subject to
          P >= 0;
          A'*P + P*A + Q <= 0;
8      cvx_end
10
11 if strcmp(cvx_status, 'Solved')
12     [eig(A), eig(A*P + P*A' + Q), eig(P)]
13 else
14     eig(A)
15 end
```

Ex. 2: DISCRETE LYAPUNOV EQ. AS SDP/LMI

Mathematical formulation

In control theory, Discrete Lyapunov equation is a condition of whether or not a discrete LTI system $\mathbf{x}_{i+1} = \mathbf{A}\mathbf{x}_i$ is stabilizable:

$$\begin{cases} \mathbf{A}^\top \mathbf{P} \mathbf{A} - \mathbf{P} + \mathbf{Q} = 0 \\ \mathbf{P} \succeq 0 \\ \mathbf{Q} \succeq 0 \end{cases} \quad (7)$$

where decision variable is \mathbf{P} . This can be represented as an SDP:

$$\begin{aligned} & \underset{\mathbf{P}}{\text{minimize}} && 0, \\ & \text{subject to} && \begin{cases} \mathbf{P} \succeq 0, \\ \mathbf{A}^\top \mathbf{P} \mathbf{A} - \mathbf{P} + \mathbf{Q} = 0. \end{cases} \end{aligned} \quad (8)$$

Ex. 2: DISCRETE LYAPUNOV EQ. AS SDP/LMI

Code

```
0 n = 7; A = 0.35*randn(n, n);  
  Q = eye(n);  
2  
  cvx_begin sdp  
4      variable P(n, n) symmetric  
      minimize 0  
6      subject to  
          P >= 0;  
          A'*P*A - P + Q <= 0;  
8  cvx_end  
10  
  if strcmp(cvx_status, 'Solved')  
12      [abs(eig(A)), eig(A'*P*A - P), eig(P)]  
  else  
14      abs(eig(A))  
  end
```

Ex. 3: FTS FOR CONTINUOUS LTI

Mathematical formulation

For an LTI system of the form $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$ there is an LMI condition to determine if it can be stabilized:

$$\begin{cases} \mathbf{A}\mathbf{P} + \mathbf{P}\mathbf{A}^\top + \mathbf{B}\mathbf{L} + \mathbf{L}\mathbf{B}^\top + \mathbf{Q} = 0 \\ \mathbf{P} \succ 0 \\ \mathbf{Q} \succ 0 \end{cases} \quad (9)$$

where decision variables are \mathbf{P} and \mathbf{L} .

This gives as a direct way to calculate linear feedback controller $\mathbf{u} = \mathbf{K}\mathbf{x}$ (note the sign!) gains:

$$\mathbf{K} = \mathbf{L}\mathbf{P}^{-1} \quad (10)$$

EX. 3: FTS FOR CONTINUOUS LTI, CODE

```
0 n = 5; m = 2;
  A = randn(n, n);
2 B = randn(n, m);
  Q = eye(n)*0.1;
4 cvx_begin sdp
    variable P(n, n) symmetric
6    variable Z(m, n)

    minimize 0
    subject to
10    P >= 0;
        A*P + P*A' + B*Z + Z'*B' + Q <= 0;
12 cvx_end
  P = full(P);
14 Z = full(Z);
  K_LMI = Z*pinv(P);
16
  disp('K_LMI eig:')
18 eig(A + B*K_LMI)
```

HOW TO DESCRIBE AN ELLIPSOID

Unit sphere transformation

Let us first remember how we describe a unit sphere:

$$\mathcal{S} = \{\mathbf{x} : \|\mathbf{x}\| \leq 1\} \quad (11)$$

An ellipsoid can be seen as a linear transformation of a unit sphere:

$$\mathcal{E} = \{\mathbf{Ax} + \mathbf{b} : \|\mathbf{x}\| \leq 1\} \quad (12)$$

HOW TO DESCRIBE AN ELLIPSOID

A dual description

Let us introduce a change of variables $\mathbf{z} = \mathbf{A}\mathbf{x} + \mathbf{b}$. Assuming \mathbf{A} is invertible, we get:

$$\mathbf{x} = \mathbf{A}^{-1}(\mathbf{z} - \mathbf{b}) \quad (13)$$

So, we can describe the exact same ellipsoid using an alternative formula:

$$\mathcal{E} = \{\mathbf{z} : \|\mathbf{B}\mathbf{z} + \mathbf{c}\| \leq 1\} \quad (14)$$

where $\mathbf{B} = \mathbf{A}^{-1}$ and $\mathbf{c} = -\mathbf{A}^{-1}\mathbf{b}$.

VOLUME OF AN ELLIPSOID

Part 1

For an ellipsoid of the form

$$\mathcal{E} = \{\mathbf{A}\mathbf{x} + \mathbf{b} : \|\mathbf{x}\| \leq 1\} \quad (15)$$

the "bigger" the \mathbf{A} , the bigger the ellipsoid. This concept can be made concrete by talking about the determinant of \mathbf{A} .

Thus, maximizing the volume of this ellipsoid is the same as maximizing $\det(\mathbf{A})$. Or, it is the same as *minimizing* the $\det(\mathbf{A}^{-1})$, since $\det(\mathbf{A}^{-1}) = 1/\det(\mathbf{A})$.

VOLUME OF AN ELLIPSOID

Part 2

For an ellipsoid of the form

$$\mathcal{E} = \{\mathbf{z} : \|\mathbf{B}\mathbf{z} + \mathbf{c}\| \leq 1\} \quad (16)$$

the "bigger" the \mathbf{B} , the *smaller* the ellipsoid. We can make it obvious by thinking that increasing \mathbf{B} leaves less room for valid \mathbf{z} , and it is the volume of valid \mathbf{z} that makes the volume of the ellipsoid in this case.

This concept can be made concrete by talking about the determinant of \mathbf{B} . Thus, maximizing the volume of this ellipsoid is the same as *minimizing* $\det(\mathbf{B})$. Or, it is the same as *maximizing* the $\det(\mathbf{B}^{-1})$.

Continue with slides from Convex Optimization — Boyd & Vandenberghe. Follow the link:

8. Geometric problems

HOMEWORK

Implement both examples from page 2 of the LMI CVX documents.

Lecture slides are available via Moodle.

You can help improve these slides at:

github.com/SergeiSa/Computational-Intelligence-Slides-Spring-2021



Check Moodle for additional links, videos, textbook suggestions.