Semidefinite Programming

Computational Intelligence, Lecture 10

by Sergei Savin

Fall 2020

Content

- Semidefinite Programming (SDP)
  - General form
  - Multiple LMI
  - SDP decision variable
- Example 1: Continuous Lyapunov equation as an SDP/LMI
  - Mathematical formulation
  - Code
- Example 2: Discrete Lyapunov equation as an SDP/LMI
  - Mathematical formulation
  - Code
- Example 3: LMI Controller design for continuous LTI
  - Mathematical formulation
  - Code
- Homework

General form of a semidefinite program is:

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

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*.

SDP can have several LMIs. Assume you have:

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

This is equivalent to:

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

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

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

where cost and constraints should adhere to SDP limitations.

Example 1: Continuous Lyapunov equation as an 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:

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

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

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

Example 1: Continuous Lyapunov equation as an SDP/LMI

Code

```
n = 7; A = randn(n, n) - 3*rand*eye(n);
Q = eye(n);

cvx_begin sdp
    variable P(n, n) symmetric
    minimize 0
    subject to
        P >= 0;
        A'*P + P*A + Q <= 0;
cvx_end

if strcmp(cvx_status, 'Solved')
    [eig(A), eig(A*P + P*A' + Q), eig(P)]
else
    eig(A)
end
```

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:

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

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

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

Example 2: Discrete Lyapunov equation as an SDP/LMI

Code

```
n = 7; A = 0.35*randn(n, n);
Q = eye(n);

cvx_begin sdp
    variable P(n, n) symmetric
    minimize 0
    subject to
        P >= 0;
        A'*P*A - P + Q <= 0;
cvx_end

if strcmp(cvx_status, 'Solved')
    [abs(eig(A)), eig(A'*P*A - P), eig(P)]
else
    abs(eig(A))
end
```

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:

$$\begin{cases} \mathbf{A}\mathbf{P} + \mathbf{P}\mathbf{A}^\top + \mathbf{B}\mathbf{L} + \mathbf{L}\mathbf{B}^\top + \mathbf{Q} = 0 \\ \mathbf{P} \succeq 0 \\ \mathbf{Q} \succeq 0 \end{cases} \tag{9}$$

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:

$$\mathbf{K} = \mathbf{L}\mathbf{P}^{-1} \tag{10}$$

Example 3: LMI Controller design for continuous LTI

Code

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

    minimize 0
    subject to
      P >= 0;
        A*P + P*A' + B*Z + Z'*B' + Q <= 0;
cvx_end
P = full(P);
Z = full(Z);
K_LMI = Z*pinv(P);

disp('K_LMI eig:')
eig(A + B*K_LMI)
```

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-Fall-2020

Check Moodle for additional links, videos, textbook suggestions.