

Robust convex programming

Convex Optimization, Lecture 11

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Consider the following problem:

Example

Find smallest $x \in \mathbb{R}$, such that $x + y \geq 1$, where $|y| \leq 2$.

In that example we need to find optimal value of x subject to a constraint where another unknown variable is present; the solution we find has to satisfy the constraint for any allowed value of y . The solution here is $x = 3$

Consider the following problem:

$$(\mathbf{a} + \delta)^\top \mathbf{x} \leq b \quad (1)$$

where δ is bounded unknown: $\|\delta\| \leq p$. It is equivalent to a linear constraint with uncertainty.

In the following slides we learn how to solve these types of problems.

ROBUST CP: LINEAR CONSTRAINT

Consider the following problem:

$$\begin{aligned} & \min_{\substack{\mathbf{x} \\ \mathbf{y}}} \text{any} \quad \|\mathbf{x}\|, \\ & \text{subject to} \quad \mathbf{c}^\top \mathbf{x} + \mathbf{d}^\top \mathbf{y} \leq h, \\ & \quad \|\mathbf{y}\| \leq p \end{aligned} \tag{2}$$

It is clear that worst-case scenario corresponds to the largest value of $\mathbf{d}^\top \mathbf{y}$. We note that

$$\max(\mathbf{d}^\top \mathbf{y}) = \max(\|\mathbf{d}\| \cdot \|\mathbf{y}\| \cdot \cos(\mathbf{d}^\wedge \mathbf{y})) = \|\mathbf{d}\|p; \text{ hence}$$
$$\mathbf{y} = p \frac{\mathbf{d}}{\|\mathbf{d}\|}.$$

ROBUST CP: LINEAR CONSTRAINT

Therefore $\mathbf{c}^\top \mathbf{x} + \mathbf{d}^\top \mathbf{y} \leq h$ becomes:

$$\mathbf{c}^\top \mathbf{x} + p\|\mathbf{d}\| \leq h \quad (3)$$

Thus our problem becomes:

$$\begin{aligned} & \min_{\mathbf{x}} && \|\mathbf{x}\|, \\ & \text{subject to} && \mathbf{c}^\top \mathbf{x} \leq h - p\|\mathbf{d}\| \end{aligned} \quad (4)$$

QUADRATIC CONSTRAINT, TYPE 1

Consider the following problem, where \mathbf{x}^* is the desired value of \mathbf{x} :

$$\begin{aligned} & \min_{\substack{\mathbf{x} \\ \mathbf{y}}} \text{any} \quad \|\mathbf{x} - \mathbf{x}^*\|, \\ & \text{subject to} \quad \mathbf{y}^\top \mathbf{Dx} \leq h, \\ & \quad \|\mathbf{y}\| \leq p \end{aligned} \tag{5}$$

This time worst-case scenario corresponds to \mathbf{y} aligned with \mathbf{Dx} and having its maximum possible length p . From that we conclude that $\mathbf{y} = p \frac{\mathbf{Dx}}{\|\mathbf{Dx}\|}$. Let us substitute it to $\mathbf{y}^\top \mathbf{Dx}$:

$$p \left(\frac{\mathbf{Dx}}{\|\mathbf{Dx}\|} \right)^\top \mathbf{Dx} = p \frac{\mathbf{x}^\top \mathbf{D}^\top \mathbf{Dx}}{\|\mathbf{Dx}\|} = p \frac{\|\mathbf{Dx}\|^2}{\|\mathbf{Dx}\|} = p \|\mathbf{Dx}\| \tag{6}$$

QUADRATIC CONSTRAINT, TYPE 1

Thus our problem becomes:

$$\begin{aligned} \min_{\mathbf{x}} \quad & \|\mathbf{x} - \mathbf{x}^*\|, \\ \text{subject to} \quad & \|\mathbf{D}\mathbf{x}\| \leq \frac{h}{p} \end{aligned} \tag{7}$$

which is an SOCP.

QUADRATIC CONSTRAINT, TYPE 2

A more general case of the previous problem is:

$$\begin{aligned} & \min_{\mathbf{x}} \text{any} \quad \|\mathbf{x} - \mathbf{x}^*\|, \\ & \text{subject to} \quad (\mathbf{y} - \mathbf{a})^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) \leq h, \\ & \quad \|\mathbf{y}\| \leq p \end{aligned} \tag{8}$$

We can rewrite $(\mathbf{y} - \mathbf{a})^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) \leq h$ as:

$$\mathbf{y}^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) - \mathbf{a}^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) \leq h \tag{9}$$

With that we see that the worse case scenario is \mathbf{y} is aligned with $\mathbf{D}(\mathbf{x} - \mathbf{b})$ and has length p :

$$\mathbf{y} = p \frac{\mathbf{D}(\mathbf{x} - \mathbf{b})}{\|\mathbf{D}(\mathbf{x} - \mathbf{b})\|} \tag{10}$$

QUADRATIC CONSTRAINT, TYPE 2

Then $\mathbf{y}^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) - \mathbf{a}^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) \leq h$ becomes:

$$p \frac{(\mathbf{x} - \mathbf{b})^\top \mathbf{D}^\top \mathbf{D}(\mathbf{x} - \mathbf{b})}{\|\mathbf{D}(\mathbf{x} - \mathbf{b})\|} - \mathbf{a}^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) \leq h \quad (11)$$

which is the same as:

$$p\|\mathbf{D}(\mathbf{x} - \mathbf{b})\| - \mathbf{a}^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) \leq h \quad (12)$$

$$\|\mathbf{D}(\mathbf{x} - \mathbf{b})\| \leq \frac{1}{p}\mathbf{a}^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) + \frac{h}{p} \quad (13)$$

which is an SOCP constraint.

QUADRATIC CONSTRAINT, TYPE 2

And thus we get:

$$\begin{aligned} \min_{\mathbf{x}} \quad & \|\mathbf{x} - \mathbf{x}^*\|, \\ \text{subject to} \quad & \|\mathbf{D}(\mathbf{x} - \mathbf{b})\| \leq \frac{1}{p} \mathbf{a}^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) + \frac{h}{p} \end{aligned} \tag{14}$$

which is SOCP.

QUADRATIC CONSTRAINT, TYPE 3

A more general case of the previous problem is:

$$\begin{aligned} & \min_{\mathbf{x}} \text{any} \quad \|\mathbf{x} - \mathbf{x}^*\|, \\ & \text{subject to} \quad (\mathbf{y} - \mathbf{a})^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) \leq h, \\ & \quad \|\mathbf{H}\mathbf{y} + \mathbf{f}\| \leq p \end{aligned} \tag{15}$$

where \mathbf{H} is has an inverse. We start by making substitution:

$$\mathbf{v} = \mathbf{H}\mathbf{y} + \mathbf{f} \tag{16}$$

meaning $\mathbf{y} = \mathbf{H}^{-1}(\mathbf{v} - \mathbf{f})$:

$$(\mathbf{H}^{-1}(\mathbf{v} - \mathbf{f}) - \mathbf{a})^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) \leq h \tag{17}$$

$$\mathbf{v}^\top \mathbf{H}^{-\top} \mathbf{D}(\mathbf{x} - \mathbf{b}) - (\mathbf{H}^{-1}\mathbf{f} + \mathbf{a})^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) \leq h \tag{18}$$

$$\mathbf{v}^\top \mathbf{H}^{-\top} \mathbf{D}(\mathbf{x} - \mathbf{b}) - (\mathbf{H}\mathbf{a} + \mathbf{f})^\top \mathbf{H}^{-\top} \mathbf{D}(\mathbf{x} - \mathbf{b}) \leq h \tag{19}$$

QUADRATIC CONSTRAINT, TYPE 3

We can introduce notation:

$$\mathbf{M} = \mathbf{H}^{-\top} \mathbf{D} \quad (20)$$

$$\mathbf{g} = \mathbf{H}\mathbf{a} + \mathbf{f} \quad (21)$$

With that we can re-write our constraint:

$$\mathbf{v}^\top \mathbf{M}(\mathbf{x} - \mathbf{b}) - \mathbf{g}^\top \mathbf{M}(\mathbf{x} - \mathbf{b}) \leq h \quad (22)$$

$$(\mathbf{v} - \mathbf{g})^\top \mathbf{M}(\mathbf{x} - \mathbf{b}) \leq h \quad (23)$$

And now we formulated type 3 problem as type 2:

$$\begin{aligned} & \min_{\mathbf{x}} \text{any} && \|\mathbf{x} - \mathbf{x}^*\|, \\ & \text{subject to} && (\mathbf{v} - \mathbf{g})^\top \mathbf{M}(\mathbf{x} - \mathbf{b}) \leq h, \\ & && \|\mathbf{v}\| \leq p \end{aligned} \quad (24)$$

QUADRATIC CONSTRAINT, TYPE 4

Try solving this problem on your own:

$$\begin{aligned} & \min_{\substack{\mathbf{x} \\ \mathbf{y}}} \text{any} \quad \|\mathbf{x} - \mathbf{x}^*\|, \\ & \text{subject to} \quad (\mathbf{y} - \mathbf{a})^\top \mathbf{D}(\mathbf{x} - \mathbf{b}) + \mathbf{s}^\top \mathbf{y} + \mathbf{q}^\top \mathbf{x} \leq h, \\ & \quad \|\mathbf{H}\mathbf{y} + \mathbf{f}\| \leq p \end{aligned} \tag{25}$$

MAX OVER NORM OF A SUM OF VECTORS

Consider the problem $\max_{\mathbf{x}} (\|\mathbf{a} + \mathbf{x}\|)$ and $\|\mathbf{x}\| \leq p$. Let us open the norm:

$$\|\mathbf{a} + \mathbf{x}\| = \sqrt{(\mathbf{a} + \mathbf{x})^\top (\mathbf{a} + \mathbf{x})} = \sqrt{\mathbf{a}^\top \mathbf{a} + 2\mathbf{a}^\top \mathbf{x} + \mathbf{x}^\top \mathbf{x}} \quad (26)$$

If \mathbf{a} is a constant, then the expression $\mathbf{a}^\top \mathbf{a} + 2\mathbf{a}^\top \mathbf{x} + \mathbf{x}^\top \mathbf{x}$ attains a maximum when $\mathbf{x}^\top \mathbf{x} = p^2$ and $\mathbf{a}^\top \mathbf{x} = \|\mathbf{a}\|p$. This implies that:

$$\mathbf{x} = p \frac{\mathbf{a}}{\|\mathbf{a}\|} \quad (27)$$

And thus:

$$\max_{\mathbf{x}} (\|\mathbf{a} + \mathbf{x}\|) = \|\mathbf{a} + p \frac{\mathbf{a}}{\|\mathbf{a}\|}\| = \|\mathbf{a}\| \left(1 + \frac{p}{\|\mathbf{a}\|}\right) = \|\mathbf{a}\| + p$$

ROBUST CP: CONIC CONSTRAINT

Consider the following problem:

$$\begin{aligned} \min_{\substack{\mathbf{x} \\ \mathbf{y}}} \quad & \text{any} \quad \|\mathbf{x} - \mathbf{x}^*\|, \\ \text{subject to} \quad & \|\mathbf{Ax} + \mathbf{b} + \mathbf{y}\| \leq \mathbf{c}^\top \mathbf{x} + d, \\ & \|\mathbf{y}\| \leq p \end{aligned} \tag{28}$$

As we discussed in the last slide, expression $\|\mathbf{Ax} + \mathbf{b} + \mathbf{y}\|$ is biggest when $\mathbf{y} = p \frac{\mathbf{Ax} + \mathbf{b}}{\|\mathbf{Ax} + \mathbf{b}\|}$, and the conic constraint becomes:

$$\|\mathbf{Ax} + \mathbf{b} + p \frac{\mathbf{Ax} + \mathbf{b}}{\|\mathbf{Ax} + \mathbf{b}\|}\| \leq \mathbf{c}^\top \mathbf{x} + d \tag{29}$$

$$\|\mathbf{Ax} + \mathbf{b}\| \left(1 + \frac{p}{\|\mathbf{Ax} + \mathbf{b}\|}\right) \leq \mathbf{c}^\top \mathbf{x} + d \tag{30}$$

ROBUST CP: CONIC CONSTRAINT

Continue the derivation:

$$\|\mathbf{Ax} + \mathbf{b}\| \left(1 + \frac{p}{\|\mathbf{Ax} + \mathbf{b}\|}\right) \leq \mathbf{c}^\top \mathbf{x} + d \quad (31)$$

$$\|\mathbf{Ax} + \mathbf{b}\| + p \leq \mathbf{c}^\top \mathbf{x} + d \quad (32)$$

Finally the problem becomes:

$$\begin{aligned} & \min_{\mathbf{x}} && \|\mathbf{x} - \mathbf{x}^*\|, \\ & \text{subject to} && \|\mathbf{Ax} + \mathbf{b}\| \leq \mathbf{c}^\top \mathbf{x} + d - p \end{aligned} \quad (33)$$

Lecture slides are available via Github, links are on Moodle:

github.com/SergeiSa/Convex-Optimization

