EN530.603 Applied Optimal Control
Lecture 3: Constrained Optimization Basics
September 14, 2020

Lecturer: Marin Kobilarov

1 Equality Constraints

In optimal control we will encounter cost functions of two variables $L : \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}$ written as

$$L(x, u)$$

where $x \in \mathbb{R}^n$ denotes the *state* and $u \in \mathbb{R}^m$ denotes the *control inputs* . We are interested in minimizing this function subject to the *equality constraints*

$$f(x, u) = \begin{bmatrix} f_1(x, u) \\ \vdots \\ f_n(x, u) \end{bmatrix} = 0.$$

Not general

In order to establish optimality conditions we first differentiate the constraint $f(x, u) = 0$ to get

$$df = \partial_x f \cdot dx + \partial_u f \cdot du = 0, \tag{1}$$

(note that we can also write the above as $\nabla_x f^T dx + \nabla_u f^T du = 0$, using the gradient notation $\nabla_x f \equiv \partial_x f^T$). Then assuming the Jacobian $\partial_x f$ is a non-singular square matrix we have

$$dx = -\partial_x f^{-1} \partial_u f \cdot du,$$

i.e. this is how small changes in u (i.e. du) must relate to small changes in x (i.e. dx). Now we have that

$$dL = \partial_x L \cdot dx + \partial_u L \cdot du = (\partial_u L - \partial_x L \; \partial_x f^{-1} \partial_u f) \, du$$

which is interpreted as the gradient of L w.r.t. u at a point where $f(x, u) = 0$ holds true. Recall that minimizing L with respect to u requires exactly that

$$\partial_u L - \partial_x L \; \partial_x f^{-1} \partial_u f = 0,$$

which is our first-order *necessary condition*. Notice that we assumed that the variables x and u are such that $\partial_x f$ is awlays nonsingular. This works well if the constraint f were linear but does not easily generalize.

不general constraint 是 linear的

1.1 The Lagrangian multiplier approach

A more general approach is to "adjoin" the constraints to the cost using "multipliers" $\lambda_1, \ldots, \lambda_n$ to form a new function

$$H(x, u, \lambda) = L(x, u) + \sum_{i=1}^{n} \lambda_i f_i(x, u) \equiv L(x, u) + \lambda^T f(x, u),$$

where H is called the *Hamiltonian.* The idea is to transform the constraint optimization of L into an unconstrained minimization of the new function H.

We will now show that minimizing H is equivalent to solving the original problem. First note that the condition $\partial_x H = 0$ is equivalent to

$$\partial_x L + \lambda^T \partial_x f = 0 \quad \Rightarrow \quad \lambda^T = -\partial_x L(\partial_x f)^{-1},$$

$\partial_x H = 0$

so we would guess that this is the solution for λ as a function of x, u (and verify it later).

Keeping $f(x, u) = 0$ fixed is equivalent to satisfying $dx = -\partial_x f^{-1} \partial_u f \cdot du$ and we have

目地是 $\nabla L = 0$ 且 $f(x)$ 满足.

$$\begin{aligned} dL &= \partial_x \cdot L dx + \partial_u L \cdot du \\ &= (-\partial_x L(\partial_x f)^{-1} \partial_u f + \partial_u L) du \\ &= (\partial_u L + \lambda^T \partial_u f) du \\ &= \partial_u H \cdot du \end{aligned} \tag{2}$$

So $\nabla H = 0 \Leftrightarrow \nabla L = 0$

Therefore, the condition $dL = 0$ when $f(x, u) = 0$ is equivalent to the *necessary optimality conditions* for $H = L(x, u) + \lambda^T f(x, u)$:

λ可由 $\nabla_x H = 0$ 求

$$\partial_\lambda H = 0 \quad \Rightarrow \quad \underline{f(x, u) = 0,} \tag{3}$$

$$\partial_x H = 0, \tag{4}$$

$$\partial_u H = 0 \tag{5}$$

$\Rightarrow \nabla H = 0$

which are $2n+m$ equations for the $2n+m$ uknowns x, u, and λ. Note that these equations are very general, e.g. they do not require finding coordinates x for which $\partial_x f$ must always be invertible.

1.1.1 Example

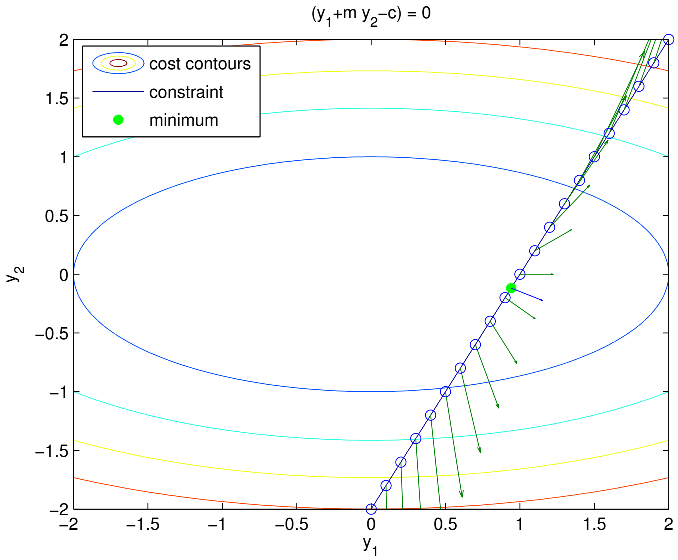
Consider $L(x, u) = \frac{1}{2} q x^2 + \frac{1}{2} r u^2$ subject to $f(x, u) = x + mu - c$, where $q > 0, r > 0, m, c$ are given constants. We have

$$\partial_x H = qx + \lambda \qquad \Rightarrow \lambda = -qx \tag{6}$$

$$\partial_u H = ru + m\lambda \qquad \Rightarrow u = -\frac{m}{r}\lambda = \frac{mq}{r}x \tag{7}$$

Substitute u into the constraint $f(x, u) = 0$ we obtain

$$x + \frac{m^2 q}{r} x - c = 0, \quad \Rightarrow \quad x = \frac{rc}{r + m^2 q}$$



$L = H - \lambda^T f$

然后 $\nabla L = 0$ $\nabla^2 L > 0$

In order to determine the *sufficient* conditions we examine the second-order expansion of $L(x, u)$. This is most conveniently accomplished using $L(x, u) = H(x, u, \lambda) - \lambda^T f(x, u)$, i.e.

$$dL \approx (\partial_x H, \partial_u H) \begin{pmatrix} dx \\ du \end{pmatrix} + \frac{1}{2}(dx^T, du^T) \begin{bmatrix} H_{xx} & H_{xu} \\ H_{ux} & H_{uu} \end{bmatrix} \begin{pmatrix} dx \\ du \end{pmatrix} - \lambda^T df$$

dL

We can substitute the constraint

$$df = 0 \quad \Leftrightarrow \quad dx = -\partial_x f^{-1} \partial_u f du$$

as well as the necessary condition $\partial_x H = 0$ to obtain

$$dL \approx \frac{1}{2} du^T [-\partial_u f^T (\partial_x f^T)^{-1},\ I] \begin{bmatrix} H_{xx} & H_{xu} \\ H_{ux} & H_{uu} \end{bmatrix} \begin{bmatrix} -\partial_x f^{-1} \partial_u f \\ I \end{bmatrix} du$$

The positive-definiteness of this quadratic form for all $du \neq 0$ at an optimal solution u^* is a *sufficient condition* for a local optimum.

1.2 The general optimization setting

More generally, assume we want to minimize $L(y)$, for $y \in \mathbb{R}^{n+m}$, subject to n equalities

$$f(y) = \begin{bmatrix} f_1(y) \\ \vdots \\ f_n(y) \end{bmatrix} = 0$$

Feasible changes dy are tangent to $f(y)$, i.e. satisfy

$$\partial_y f \cdot dy = 0,$$

which can also be equivalently written using gradient notation as:

$$\nabla f_i^T dy = 0, \quad \text{for all} \quad i = 1, \cdots, n.$$

$y = x \times u$

We will employ geometric reasoning to obtain the optimality conditions. First, note that directions orthogonal to any feasible dy must be spanned by the gradients $\{\nabla f_1, \cdots, \nabla f_n\}$. At an optimum y^* we must also have

$$\boxed{\nabla L(y^*)^T dy = 0,}$$

first order necessary cond

i.e. ∇L is orthogonal to any feasible dy and must be spanned by gradients as well. This can be expressed as:

dy 一定与 $\nabla f_i(y^*)$ 垂直

$$\boxed{\nabla L(y^*) = -\sum_{i=1}^{n} \lambda_i^* \nabla f_i(y^*)}$$

get

where the minus sign is by convention, and the scalars λ_i can be arbitrary. Therefore, we have

get dy

$$\boxed{\nabla L(y^*) + \sum_{i=1}^{n} \lambda_i^* \nabla f_i(y^*) = 0 :} \quad \text{:first-order necessary conditions}$$

$\nabla L(y^*)\, dy = 0$

along with

$$\boxed{dy^T \left[\nabla^2 L(y^*) + \sum_{i=1}^{n} \lambda_i^* \nabla^2 f_i(y^*) \right] dy \geq 0,} \quad \text{:second-order necessary conditions}$$

then constitute the necessary conditions for optimality. Note that in the above dy is not arbitrary, i.e. we require that $\nabla f_i(y^*)^T dy = 0$ for all $i = 1, ..., n$.

Sufficient conditions for a strict local optimum are obtained by requiring the positive-definiteness of the quadratic form above.

Finally, note that the multipliers are related to the solution *sensitivity*. The relationship

$$\nabla L = -\sum_{i=1}^{n} \lambda_i \nabla f_i$$

signifies that the multupliers are, roughly speaking, the ratio of the change in cost to the change in constraint. In other words, the i-th multiplier λ_i determines how changes in the i-th constraint f_i relate to changes in the cost L as a result of perturbing the solution by dy.

2 Checking Sufficient Conditions in practice

A common algebraic way to check the sufficient conditions is through QR decomposition of the constraint gradient. In particular, we have that

$$\nabla f^T dy = 0 \quad \Rightarrow \quad dy \in \text{Null}(\nabla f^T) \tag{8}$$

and finding the null space can be accomplished using the QR decomposition of ∇f, i.e.

$$\nabla f = Q \begin{bmatrix} R \\ 0 \end{bmatrix}.$$

where $Q \in \mathbb{R}^{n \times n}$ is such that $Q^T Q = I$ and $R \in \mathbb{R}^{m \times m}$ is upper triangular. Therefore, any dy of the form

$$dy = Q \begin{bmatrix} 0 \\ du \end{bmatrix},$$

for some arbitary $du \in \mathbb{R}^{n-m}$ would satsfiy (8). If we decompose Q according to

$$Q = \begin{bmatrix} Q_1 & Q_2 \end{bmatrix},$$

where $Q_1 \in \mathbb{R}^{n\times m}$ and $Q_2 \in \mathbb{R}^{n\times(n-m)}$, then dy can be expressed using the last $n-m$ columns in Q as

$$dy = Q_2 du,$$

which leads to the sufficient conditions

$$du^T Q_2^T \left[\nabla^2 L(y^*) + \sum_{i=1}^{m} \lambda_i \nabla^2 f(y^*)\right] Q_2 du > 0,$$

for arbitrary $du \neq 0$, i.e. it reduces to checking that the quadratic matrix $Q_2^T \left[\nabla^2 L(y^*) + \sum_{i=1}^{m} \lambda_i \nabla^2 f(y^*)\right] Q_2$ is positive definite.

Example

Consider the minimization of $L(y) = \frac{1}{2}(y_1^2 + y_2^2) + a x_1 x_2$ subjec to $f = y_1 - y_2 = 0$ for some constant a. We have

$$\nabla L = \begin{bmatrix} y_1 + a y_2 \\ a y_1 + y_2 \end{bmatrix}, \qquad \nabla f = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

and

$$\nabla^2 L = \begin{bmatrix} 1 & a \\ a & 1 \end{bmatrix}, \qquad \nabla^2 f = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The eigenvalues of $\nabla^2 L$ are $1 \pm a$, so for $a = 1$ the Hessian is positive semi-definite and for $|a| > 1$ it has negative eigenvalues. Thus we need to inspect the constrained Hessian, i.e. the Hessian along direction dy consistent with the constraint. This can be accomplished by expressing dy as

$$dy = \begin{bmatrix} 1 \\ 1 \end{bmatrix} du,$$

for some arbitary du, based on which we have

$$dy^T \left[\nabla^2 L + \lambda \nabla^2 f_i\right] dy = du \begin{bmatrix} 1 \\ 1 \end{bmatrix}^T \begin{bmatrix} 1 & a \\ a & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} du,$$

and since du is arbitrary we now need to check whether

$$\begin{bmatrix} 1 \\ 1 \end{bmatrix}^T \begin{bmatrix} 1 & a \\ a & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = (2 + 2a)$$

is positive definite, which is true as long as $a > -1$. Note that we obtained a condition on a which is less strict than the condition on the unconstrained Hessian above. The reason is that we only care about the behavior of the cost long constraint directions.

3 Inequality Constraints

Inequality constraints are used to encode allowable regions in state and control space. A general class of problems with such constraints involve the minimization of

$$L(y)$$

subject to

$$f(y) \leq 0,$$

where f can be of any dimension. Let y^* be the unconstrained minimum of $L(y)$. If the constrained is not voiolated, i.e. if $f(y^*) \leq 0$ then problem is solved. If we have that

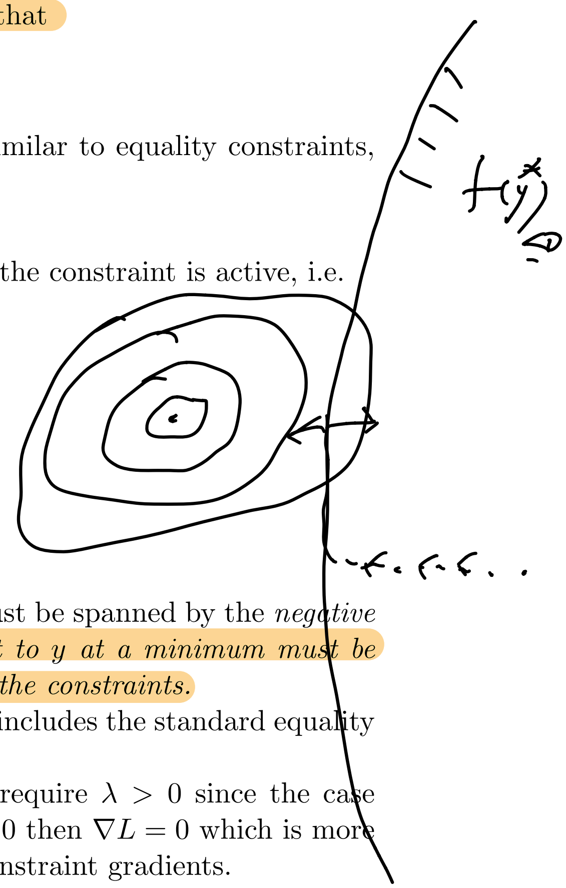
$$f(y^*) > 0,$$

then we say that the constraints are *active* and must be enforced similar to equality constraints, i.e. using the Hamiltonian

$$H(y, \lambda) = L(y) + \lambda^T f(y),$$

with the main difference that the multipliers must be positive when the constraint is active, i.e.

$$\lambda = \begin{cases} \geq 0, & f(y) = 0, \\ = 0, & f(y) < 0. \end{cases}$$



The condition $H_y = 0$ is equivalent to the relationship

$$\nabla L = -\sum_{i=1}^{n} \lambda_i \nabla f_i$$

which now has the geometric interpretation that the cost gradient must be spanned by the *negative* constraint gradients. In other words, *the gradient of L with respect to y at a minimum must be pointed in such a way that decrease of L can only come by violating the constraints.*

The *sufficient condition* for local minimum of $L(y)$ with $f(y) \leq 0$ includes the standard equality constraint conditions to which we add the condition that all $\lambda > 0$.

Note: when the constraint is active we let $\lambda \geq 0$ rather than require $\lambda > 0$ since the case $\lambda = 0$ might also satisfy the necessary conditions. In fact, when $\lambda = 0$ then $\nabla L = 0$ which is more restrictive than only requiring the cost gradient to be spanned by constraint gradients.

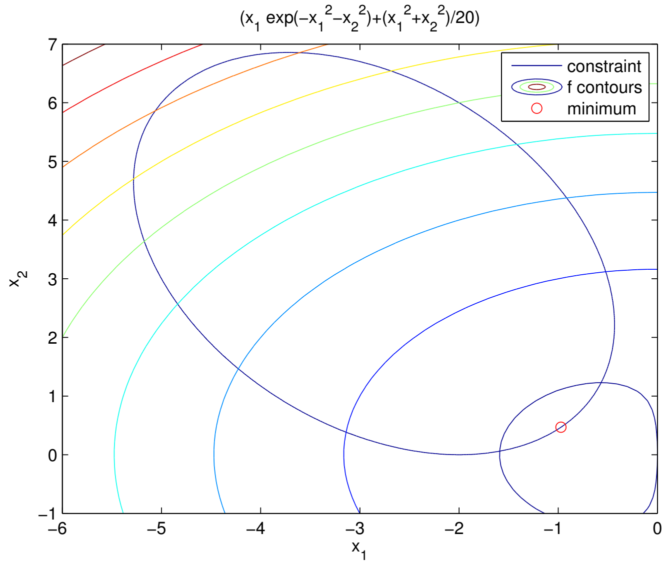
3.1 Example

Consider the function $f : \mathbb{R}^2 \to \mathbb{R}$

$$L(x) = x_1 \exp(-(x_1^2 + x_2^2)) + (x_1^2 + x_2^2)/20$$

subject to the inequality constraint

$$f(x) = x_1 x_2/2 + (x_1 + 2)^2 + (x_2 - 2)^2/2 - 2 \leq 0$$



See *lecture3_2.m*