EN530.603 Applied Optimal Control
Lecture 3: Constrained Optimization Basics
September 11, 2013

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*

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

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

$$df = f_x \cdot dx + f_u \cdot du = 0, \tag{1}$$

Then assuming f_x is a non-singular square matrix

$$dx = -f_x^{-1} f_u \cdot du,$$

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

$$dL = L_x \cdot dx + L_u \cdot du = (L_u - L_x\ f_x^{-1} f_u)\, du$$

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

$$L_u - L_x\ f_x^{-1} f_u = 0,$$

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

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

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

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 $H_x = 0$ is equivalent to

$$L_x + \lambda^T f_x = 0 \quad \Rightarrow \quad \lambda^T = -L_x (f_x)^{-1},$$

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 $dx = -f_x^{-1} f_u \cdot du$ and we have

$$\begin{aligned} dL &= L_x dx + L_u du \\ &= (-L_x (f_x)^{-1} f_u + L_u) du \\ &= (L_u + \lambda^T f_u) du \\ &= H_u \cdot du \end{aligned} \tag{2}$$

Therefore $L_u = H_u$ when $f(x, u) = 0$ holds and the *necessary optimality conditions* are

$$f(x, u) = 0, \tag{3}$$

$$\partial_x H = 0, \qquad \text{where } H = L(x, u) + \lambda^T f(x, u) \tag{4}$$

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

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 f_x must always be invertible.

1.1.1 Example

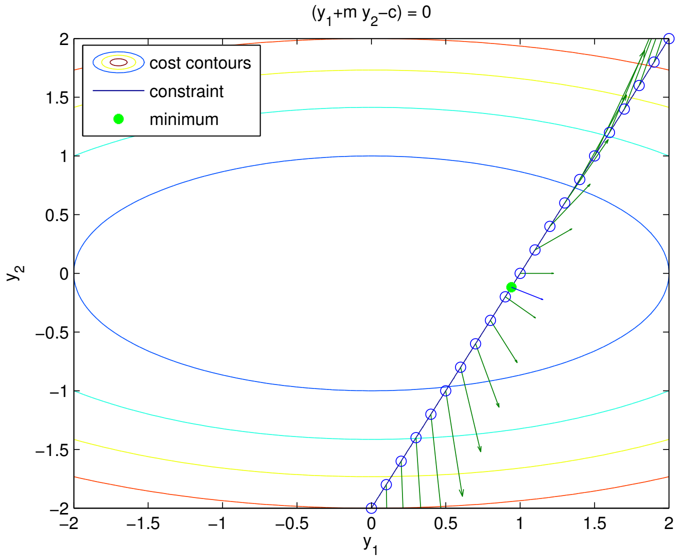
Consider $L(x, u) = \frac{1}{2} q x^2 + \frac{1}{2} r u^2$ subject to $f(x, u) = x + mu - c$, where $q > 0, r > 0, m, c$ are given constants. We have

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

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

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

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



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.

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

We can substitute the constraint

$$df = 0 \quad \Leftrightarrow \quad dx = -f_x^{-1} f_u du$$

as well as the necessary condition $H_x = 0$ to obtain

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

The positive-definiteness of this quadratic form for all $du = 0$ 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

$$f_y \cdot dy = 0.$$

We will employ geometric reasoning to obtain 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 have

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

i.e. ∇L is orthogonal to any feasible dy and must be spanned by gradients as well, i.e.

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

where the minus sign is by convention.

We have

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

along with

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

where $\nabla f(y^*)^T dy = 0$ then constitute the necessary conditions for optimality. 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 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 $\lambda > 0$.

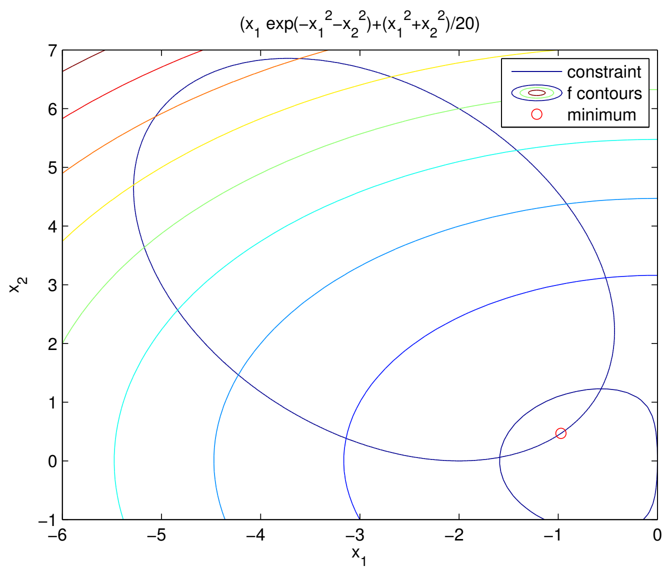
2.1 Example

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*

References