

Pontryagin's maximum principle

Theory summary and applications

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1 Preliminary definitions

1.1 Control System

A **control system** is a triple $\Sigma = (\chi, f, U)$, where

1. χ , representing the state of the system, is an **pen** subset of \mathbb{R}^n , $\chi \subset \mathbb{R}^n$.
2. U , representing the space of possible (*instantaneous*) controls, is an open subset of \mathbb{R}^m , $U \subset \mathbb{R}^m$
3. $f : \chi \times cl(U) \rightarrow \mathbb{R}^n$ is a function which dictates the law with which the system evolves. f
 - (a) is continuous
 - (b) the map $x \rightarrow f(x, u)$ is of class C^1 for each $u \in cl(U)$

Since f is function of the current state of the system and of the current control, the system's evolution does not explicitly depends on time. Of course, the law dictating the evolution of the system's status is

$$\dot{\xi}(t) = f(\xi(t), \mu(t)) \quad (1.1)$$

where obviously, for for each t , $\xi(t) \in \chi$ is the "current" (at time t) state of the system, and $\mu(t) \in U$ is the current (at time t) control, dictated by the control law $\mu(t)$.

1.2 Control and Trajectories

The idea here is that we want some limitations on the function $t \rightarrow \mu(t)$, because, starting from a certain state, we want the control to originate, through 1.1, trajectories that, at least, "makes sense". So, given a control system $\Sigma = (\chi, f, U)$ we define

- An **admissible control** is a *measurable* map $\mu : I \rightarrow U$ where I is a (time) interval $I \subset \mathbb{R}$, and such that $t \rightarrow f(x, \mu(t))$ is locally integrable for each $x \in \chi$
- we denote the set of admissible control defined on time interval I by $\mathfrak{U}(I)$
- A **controlled trajectory** is a pair (ξ, μ) where, for some time interval $I \in \mathbb{R}$
 - $\mu \in \mathfrak{U}(I)$ is then a function expressing the control through which the system is driven in the time interval, and is an admissible control. This map will be simply be referred to as the **control**.
 - $\xi : I \rightarrow \chi$ is the map linking the times in the interval to their corresponding state, which follows the law 1.1. This map will be referred to as the **trajectory**.
- a **controlled arc** is a controlled trajectory defined on a compact time interval.

The set of the controlled trajectories for a given control system $\Sigma = (\chi, f, U)$ is named $\text{Ctraj}(\Sigma)$, the set of the controlled arcs for the control system is named $\text{Carc}(\Sigma)$

1.3 Lagrangian, costs and optimal control problem(s)

Since we will want to optimize a cost, we first have to define this objective function which has to be minimized. This will be the integral of another function, the lagrangian, along the path of the system in its evolution from the *beginning* to the *end* of the syof another function (Note: the integral is actually calculated by integrating on the time interval associated with the a controlled trajectory, so it's integrated on an interval of \mathbb{R} , not along a path in \mathbb{R}^n). So, given a control system $\Sigma = (\chi, f, U)$

- A **Lagrangian** for Σ is a function $L : \chi \times cl(U) \rightarrow \mathbb{R}$ such that
 - L is continuous
 - the function $x \rightarrow L(x, u)$ is of class C^1 for each $u \in cl(U)$
- given a Lagrangian L , it is said that a controlled trajectory (ξ, μ) with relative time interval I is **L-acceptable** if the function $t \rightarrow L(\xi(t), \mu(t))$ is integrable.
- given a Lagrangian L , the corresponding **objective function** is the map $J_{\Sigma, L} : \text{Ctraj}(\Sigma) \rightarrow \overline{\mathbb{R}}$ given by

$$J_{\Sigma, L}(\xi, \mu) = \int_I L(\xi(t), \mu(t)) dt \quad (1.2)$$

where we pose $J_{\Sigma, L} = \infty$ if (ξ, μ) is not L-acceptable (if it's not integrable). The set of L-acceptable controlled trajectories (arcs) for the control system is denoted as $\text{Ctraj}(\Sigma, L)$ (or $\text{Carc}(\Sigma, L)$)

The idea here is that one should seek to minimize the objective function, with the "variable" to be tuned being the controlled trajectory. Usually though the problem faced is such that the system will start his evolution in a certain initial state, which resides in a set of possible initial conditions S_0 , and some end conditions will be given, which means that in the end, the state of the system should reside in another set, S_1 . Of course $S_0, S_1 \subset \chi$. We thus call $\text{Carc}(\Sigma, L, S_0, S_1)$ the set of controlled arcs for the control system $\Sigma = (\chi, f, U)$ with Lagrangian L , which have also the following properties

- every (ξ, μ) in $\text{Carc}(\Sigma, L, S_0, S_1)$ is defined on a time interval of the form $[t_0, t_1]$ with $t_0 < t_1; t_0, t_1 \in \mathbb{R}$
- every (ξ, μ) in $\text{Carc}(\Sigma, L, S_0, S_1)$ then the said controlled arc is also in $\text{Carc}(\Sigma, L)$, which means it is an L -acceptable controlled arc
- every (ξ, μ) in $\text{Carc}(\Sigma, L, S_0, S_1)$ defined on the time interval $[t_0, t_1]$ then $\chi(t_0) \in S_0$ and $\chi(t_1) \in S_1$.

Now we can precisely define the optimization problem. There are actually two of these problem, depending on the fact that t_0, t_1 may or may not be fixed. We are going to consider the demonstration for the fixed interval one. So,

Free interval optimal control problem Let's have

- a control system $\Sigma = (\chi, f, U)$,
- a Lagrangian L ,
- $S_0, S_1 \in \chi$ sets,

then a controlled trajectory $(\xi_*, \mu_*) \in \text{Carc}(\Sigma, L, S_0, S_1)$ is a **solution to the free interval optimal control problem** if

$$\forall (\xi, \mu) \in \text{Carc}(\Sigma, L, S_0, S_1), J_{\Sigma, L}(\xi_*, \mu_*) < J_{\Sigma, L}(\xi, \mu).$$

The set of all the possible solutions is denoted as $\mathfrak{P}(\Sigma, L, S_0, S_1)$.

Fixed interval optimal control problem Let's have

- a control system $\Sigma = (\chi, f, U)$,
- a Lagrangian L ,
- $S_0, S_1 \in \chi$ sets,
- a time interval $[t_0, t_1]$ with $t_0 < t_1; t_0, t_1 \in \mathbb{R}$

then a controlled trajectory $(\xi_*, \mu_*) \in \text{Carc}(\Sigma, L, S_0, S_1, [t_0, t_1])$ is a **solution to the fixed interval optimal control problem** if

$$\forall (\xi, \mu) \in \text{Carc}(\Sigma, L, S_0, S_1, [t_0, t_1]), J_{\Sigma, L}(\xi_*, \mu_*) < J_{\Sigma, L}(\xi, \mu).$$

The set of all the possible solutions is denoted as $\mathfrak{P}(\Sigma, L, S_0, S_1, [t_0, t_1])$.

A simple example The problem in which the cost is the time with which the system is driven from S_0 to S_1 is simply a free interval optimal control problem, in which there is a control system with Lagrangian $L(x, u) = 1$.

1.4 Hamiltonians

The maximum principle is related with the maximization of a Hamiltonian associated with a control system with a certain Lagrangian, so we have the following definitions.

Let $\Sigma = (\chi, f, U)$ be a control system, L a Lagrangian, then

- the **Hamiltonian** is the function $H_\Sigma : \chi \times \mathbb{R}^n \times U \rightarrow \mathbb{R}$ given by

$$H_\Sigma(x, p, u) = \langle p, f(x, u) \rangle$$

- the **extended Hamiltonian** is the function $H_{\Sigma, L} : \chi \times \mathbb{R}^n \times U \rightarrow \mathbb{R}$ given by

$$H_{\Sigma, L}(x, p, u) = \langle p, f(x, u) \rangle + L(x, u) = H_\Sigma(x, p, u) + L(x, u)$$

- the **maximum Hamiltonian** is the function $H_\Sigma^{max} : \chi \times \mathbb{R}^n \rightarrow \overline{\mathbb{R}}$ given by

$$H_\Sigma^{max} = \sup\{H_\Sigma(x, p, u) | u \in U\}$$

- the **maximum extended Hamiltonian** is the function $H_{\Sigma, L}^{max} : \chi \times \mathbb{R}^n \rightarrow \overline{\mathbb{R}}$ given by

$$H_{\Sigma, L}^{max} = \sup\{H_{\Sigma, L}(x, p, u) | u \in U\}$$

- the variable p is sometimes called **costate**

1.5 Adjoint response

There are another two quantities, namely the adjoint response and the control variations (with the associated variational equation), which are very important in the understanding of the maximum principle. The part relative to adjoint response will now be stated, because it appears in the statement of the principle, while the part concerning brings along concepts that are useful to the demonstration and to the understanding of the geometrical significance of the principle.

So now let $\Sigma = (\chi, f, U)$ be a control system, and

- $(\xi, \mu) \in Ctraj(\Sigma)$ be a controlled trajectory with time interval I , then we define the **adjoint response** for Σ along (ξ, μ) as a locally absolutely

continous map $\lambda : I \rightarrow \mathbb{R}^n$ which also satisfies the following differential equation(s):

$$\begin{aligned}\dot{\xi}(t) &= \mathbf{D}_2 H_\Sigma(\xi(t), \lambda(t), \mu(t)) (= f(x, u)) \\ \lambda(t) &= -\mathbf{D}_1 H_\Sigma(\xi(t), \lambda(t), \mu(t))\end{aligned}\tag{1.3}$$

we will see later that this last equation can reach another equivalent form.

- if L is a Lagrangian and $(\xi, \mu) \in Ctraj(\Sigma, L)$ is an L -acceptable controlled trajectory with time interval I , we then define the **adjoint response** for (Σ, L) along (ξ, μ) as a locally absolutely continous map $\lambda : I \rightarrow \mathbb{R}^n$ which also satisfies the following differential equation(s):

$$\begin{aligned}\dot{\xi}(t) &= \mathbf{D}_2 H_{\Sigma, L}(\xi(t), \lambda(t), \mu(t)) (= f(x, u)) \\ \lambda(t) &= -(D_1 H_{\Sigma, L}(\xi(t), \lambda(t), \mu(t)))\end{aligned}\tag{1.4}$$

1.6 Smooth constraint sets

Part of the maximum principle deals with the case in which S_0 and S_1 are "smooth", so we might define a **smooth constraint set** S as a subset of the set of possible (control)system states $S \subset \chi$ such that there exists a C^1 function $\Phi : \chi \rightarrow \mathbb{R}^k$, such that $S = \Phi^{-1}(0)$ and also $D\Phi(x)$ is surjective for each $x \in S$

2 Statement of the maximum Principle

2.1 Maximum principle for free interval problems

Let $\Sigma = (\chi, f, U)$ be a control system, L a Lagrangian, S_0 and S_1 subsets of χ . A necessary condition for a controlled trajectory (ξ_*, μ_*) defined on $[t_0, t_1]$ to be optimal, that is, a necessary condition so that $(\xi_*, \mu_*) \in \mathfrak{P}(\Sigma, L, S_0, S_1)$ is the existence of an absolutely continuous map $[t_0, t_1] : [t_0, t_1] \rightarrow \mathbb{R}^n$ and of $\lambda_*^0 \in \{-1, 0\}$ that have also the following properties

1. either $\lambda_*^0 = .1$ or $\lambda_*(t_0) \neq 0$
2. λ_* is an adjoint response for (Σ, λ_*^0, L) along (ξ_*, μ_*)
3. $H_{\Sigma, \lambda_*^0, L}(\xi_*(t), \lambda_*(t), \mu_*(t)) = H_{\Sigma, \lambda_*^0, L}^{max}(\xi_*(t), \lambda_*(t))$ for almost every $t \in [t_0, t_1]$

If μ_* is bounded, then

4. $\forall t \in [t_0, t_1] \ H_{\Sigma, \lambda_*^0, L}^{max}(\xi_*(t), \lambda_*(t)) = 0$

If, S_1 and S_0 are smooth constraint sets, then $[t_0, t_1]$ can be chosen such that

5. $\lambda_*(t_0)$ is orthogonal to $\ker(\mathbf{D}\Phi_0(\xi(t_0)))$ and $\lambda_*(t_1)$ is orthogonal to $\ker(\mathbf{D}\Phi_1(\xi(t_1)))$

For the fixed interval problem only condition 4 is lost.

2.2 Maximum principle for fixed interval problems

Let $\Sigma = (\chi, f, U)$ be a control system, L a Lagrangian, S_0 and S_1 subsets of χ ; $[t_0, t_1] \subset \mathbb{R}$ an interval. A necessary condition for a controlled trajectory (ξ_*, μ_*) defined on $[t_0, t_1]$ to be optimal, that is, a necessary condition so that $(\xi_*, \mu_*) \in \mathfrak{P}(\Sigma, L, S_0, S_1, [t_0, t_1])$ is the existence of an absolutely continuous map $[t_0, t_1] : [t_0, t_1] \rightarrow \mathbb{R}^n$ and of $\lambda_*^0 \in \{-1, 0\}$ that have also the following properties

1. either $\lambda_*^0 = -1$ or $\lambda_*(t_0) \neq 0$
2. λ_* is an adjoint response for (Σ, λ_*^0, L) along (ξ_*, μ_*)
3. $H_{\Sigma, \lambda_*^0, L}(\xi_*(t), \lambda_*(t), \mu_*(t)) = H_{\Sigma, \lambda_*^0, L}^{max}(\xi_*(t), \lambda_*(t))$ for almost every $t \in [t_0, t_1]$

If, S_1 and S_0 are smooth constraint sets, then $[t_0, t_1]$ can be chosen such that

4. $\lambda_*(t_0)$ is orthogonal to $\ker(\mathbf{D}\Phi_0(\xi(t_0)))$ and $\lambda_*(t_1)$ is orthogonal to $\ker(\mathbf{D}\Phi_1(\xi(t_1)))$

3 Hint of demonstration

the first step we need to take is analyzing the effect of varying a trajectory first. In general, one can expect to vary trajectory followed by the state of a control system in two ways: given a control, varying the initial conditions or, given the initial conditions, varying the control. Nevertheless it is still necessary to develop some tools to *describe* the variation of the trajectory in some ways.

3.1 Variations and adjoint response

Variational and adjoint equations

Given a control system $\Sigma = (\chi, f, U)$ and an admissible control $\mu : I \rightarrow U$ we have

- the **variational equation** for Σ with control μ is the differential equation

$$\begin{aligned} \dot{\xi}(t) &= f(\xi(t), \mu(t)); \\ \dot{v}(t) &= \mathbf{D}_1 f(\xi(t), \mu(t)) \cdot v(t) \\ (\xi(t), \mu(t)) &\in (\chi \times \mathbb{R}^n) \end{aligned} \tag{3.1}$$

- the **variational equation** for Σ with control μ is the differential equation

$$\begin{aligned}\dot{\xi}(t) &= f(\xi(t), \mu(t)); \\ \dot{\lambda}(t) &= -D_1 f^T(\xi(t), \mu(t)) \cdot v(t) \\ (\xi(t), \lambda(t)) &\in (\chi \times \mathbb{R}^n)\end{aligned}\tag{3.2}$$

interpretation It is straightforward to see that the variational equation describes, through a linearization, the evolution in time of a small (infinitesimal) variation from the original trajectory $\xi(t)$, which is one of the solutions to the equation 1.1.

Obviously, it is hoped that, given a certain control and initial condition, the solution to 1.1 is unique, but a-priori it cannot be said.

The geometrical interpretation of the adjoint equation is more subtle, but, in a naive way, one could say that, given an optimal trajectory, the adjoint response is a vector orthogonal to the hyperplane given by (directions of the)the possible (infinitesimal) variations to that trajectory.

3.2 Variation and infinitesimal variation

Definitions

Let $\Sigma = (\chi, f, U)$ be a control system, $x_0 \in \chi$ be an initial condition for eq. 1.1, $[t_0, t_1] \subset \mathbb{R}$ a time interval, $\mu \in \mathfrak{U}(x_0, t_0, [t_0, t_1])$. a **variation** of the trajectory $\xi(\mu, x_0, t_0, \cdot)$ is map $\sigma : J \times [t_0, t_1] \rightarrow \chi$ with the following properties

- $J \subset \mathbb{R}; 0 \in \text{int}(J)$ is an interval for which zero reside in its internal part
- $\sigma(0, t) = \xi(\mu, x_0, t_0, t)$ for each $t \in [t_0, t_1]$
- $s \rightarrow \sigma(s, t)$ is of class C^1 for each $t \in [t_0, t_1]$
- $t \rightarrow \sigma(s, t)$ is a solution of eq. 1.1.

Given a variation and it's relative "original" trajectory, there is another important quantity, which is the corresponding **infinitesimal variation**. This is yet another map defined with the following limit

$$\delta\sigma(t) = \left. \frac{d}{ds} \right|_{s=0} \sigma(s, t).\tag{3.3}$$

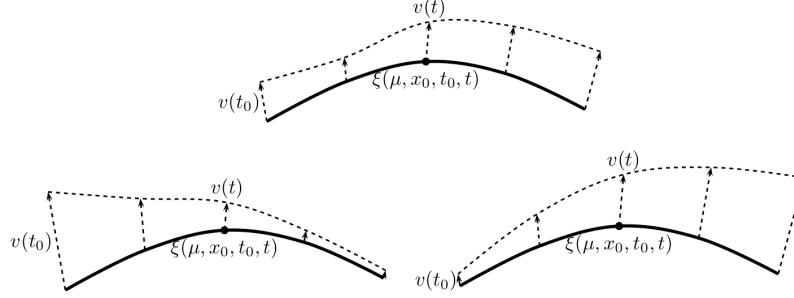


Figure 1:

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The dotted arrow represent the difference between the variation (at various times and at a given s), and the "original" trajectory, at the same time. The infinitesimal variation is then represented by a vector such that, at a given time \bar{t} , $\sigma(s, \bar{t}) \approx \xi(\mu, x_0, t_0, \bar{t}) + \delta\sigma(\bar{t}) * s$. Actually, there is another interpretation to the image, in which the dotted arrow are the vectors represent the **infinitesimal** variations, and the dotted line is just the envelope of the dotted arrows calculated at different times. In this case, the dotted part and the continuous-line of the figure have scales that have nothing to do one with each other. Nevertheless, in both interpretations, it is possible to understand the concept of a stable, unstable and "indifferent" trajectory, in which a disturbance in the trajectory is amplified rather than muted.

A theorem about infinitesimal variations Here it will be stated that if a map is solution of equation 3.1 then it is an infinitesimal variation, and vice versa.

Let $\Sigma = (\chi, f, U)$ be a control system, $x_0 \in \chi$ be an initial condition for eq. 1.1, $[t_0, t_1] \subset \mathbb{R}$ a time interval, $\mu \in \mathcal{U}(x_0, t_0, [t_0, t_1])$. Given a map $v : [t_0, t_1] \rightarrow \mathbb{R}^n$ the statements

- there exists a map σ which is a variation of $\xi(\mu, x_0, t_0, \cdot)$ such that $v = \delta\sigma$;
- $t \rightarrow (\xi(\mu, x_0, t_0, t), v(t))$ satisfies the variational equation 3.1.

are equivalent.

The fundamental matrix Φ During the demonstration of the preceding theorem, an $n \times n$ linear map $\Phi(t) : \mathbb{R}^n \rightarrow \mathbb{R}^n$ has been defined, as a map such that $\Phi(t) \cdot = D_2\xi(\mu, x_0, t_0, t) \cdot w$.

By differentiation one can see that $\Phi(t)$ satisfies this matrix differential initial value problem:

$$\dot{\Phi}(t) = D_1f(\xi(\mu, x_0, t_0, t), \mu(t)) \circ; \quad \Phi(t_0) = Id_{n \times n}$$

We thus define $\Phi(\mu, x_0, t_0, \tau, t)$ as the solution to the matrix initial value problem

$$\dot{\Phi}(t) = D_1 f(\xi(\mu, x_0, t_0, t), \mu(t)) \circ; \quad \Phi(\tau) = Id_{n \times n} \dots$$

The importance of this matrix resides in the fact that, being the variational equation 3.1 a linear one and being Φ the fundamental matrix of the equation, it is true that, for a variation $v(t)$ (which is also a solution to the variational equation, because of the theorem), $v(t) = \Phi(\mu, x_0, t_0, t_0, t) \cdot v(t_0)$
 Φ also has some properties, about the composition of the

3.3 Properties of adjoint response

Hamilton's and adjoint equation

Adjoint response and variations

A corollary

Fundamental matrix for the adjoint response

3.4 Needle variations

4 Moon landing problem