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# Optimal control under probability constraint

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# Presentation outline

- 1 Problem formulation
- 2 Modeling improvement
- 3 Stochastic Arrow-Hurwicz algorithm
- 4 Numerical results

- 1 Problem formulation
  - Satellite model and deterministic optimization problem
  - Engine failure
  - Stochastic formulation
- 2 Modeling improvement
- 3 Stochastic Arrow-Hurwicz algorithm
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## Satellite model

$$\frac{dr}{dt} = v, \quad \frac{dv}{dt} = -\mu \frac{r}{\|r\|^3} + \frac{F}{m} \kappa, \quad (1a)$$

$$\frac{dm}{dt} = -\frac{T}{g_0 I_{sp}} \delta. \quad (1b)$$

(1a) : 6-dimensional state vector (position  $r$  and velocity  $v$ ).

(1b) : 1-dimensional state vector (mass  $m$  including fuel).

$\kappa$  involves the direction cosines of the thrust and the on-off switch  $\delta$  of the engine (3 controls), and  $\mu, F, T, g_0, I_{sp}$  are constants.

The deterministic control problem is to drive the satellite from the initial condition at  $t_i$  to a known **final position  $r_f$  and velocity  $v_f$**  at  $t_f$  (given) while **minimizing fuel consumption  $m(t_i) - m(t_f)$** .

## Deterministic optimization problem

Using **equinoctial coordinates** for the position and velocity

↷ **state vector**  $x \in \mathbb{R}^7$ ,

and **cartesian coordinates** for the thrust of the engine

↷ **control vector**  $u \in \mathbb{R}^3$ ,

the deterministic optimization problem is written as follows:

$$\min_{u(\cdot)} K(x(t_f)) \quad (2a)$$

subject to:

$$x(t_i) = x_i, \quad \dot{x}(t) = f(x(t), u(t)), \quad (2b)$$

$$\|u(t)\| \leq 1 \quad \forall t \in [t_i, t_f], \quad (2c)$$

$$C(x(t_f)) = 0. \quad (2d)$$

## Engine failure

- Sometimes, the engine may **fail to work** when needed: the satellite **drift away** from the deterministic optimal trajectory. After the engine control is recovered, it is not always possible to **drive the satellite to the final target** at  $t_f$ .
- By **anticipating** such possible failures and by **modifying** the trajectory followed **before** any such failure occurs, one may **increase** the possibility of eventually reaching the target. But such a deviation from the deterministic optimal trajectory results in a **deterioration of the economic performance**.
- The problem is thus to **balance** the **increased probability** of eventually reaching the target despite possible failures against the **expected economic performance**, that is, to **quantify** the price of safety one is ready to pay for.

## Stochastic formulation (1)

A failure is modeled using two random variables:

- $\mathbf{t}_p$  : random initial time of the failure,
- $\mathbf{t}_d$  : random duration of the failure.

For every realization  $(t_p^\xi, t_d^\xi)$ :

- ①  $u(\cdot)$  denotes the control used prior to any failure  
 $\rightsquigarrow u$  is defined over  $[t_i, t_f]$  but implemented over  $[t_i, t_p^\xi]$   
 and corresponds to an **open-loop control**,
- ② the control is 0 in  $[t_p^\xi, t_p^\xi + t_d^\xi]$ ,
- ③  $v^\xi(\cdot)$  denotes the control used after the end of the failure  
 $\rightsquigarrow v^\xi$  is defined over  $[t_p^\xi + t_d^\xi, t_f]$  (if nonempty)  
 and corresponds to a **closed-loop strategy v**.

The **satellite dynamics** in the stochastic formulation writes:

$$x^\xi(t_i) = x_i, \quad \dot{x}^\xi(t) = f^\xi(x^\xi(t), u(t), v^\xi(t)).$$



## Stochastic formulation (2)

The problem is to minimize the **expected cost** (fuel consumption)

- w.r.t. the open-loop control  $u$  and the closed-loop strategy  $\mathbf{v}$ ,
- the **probability to hit the target** at time  $t_f$  being at least  $p$ .

$$\min_{u(\cdot)} \mathbb{E} \left( \min_{\mathbf{v}^\xi(\cdot)} K(x^\xi(t_f)) \right) \quad (3a)$$

subject to:

$$x^\xi(t_i) = x_i, \quad \dot{x}^\xi(t) = f^\xi(x^\xi(t), u(t), \mathbf{v}^\xi(t)), \quad (3b)$$

$$\|u(t)\| \leq 1 \quad \forall t \in [t_i, t_f], \quad \|\mathbf{v}^\xi(t)\| \leq 1 \quad \forall t \in [t_p^\xi + t_d^\xi, t_f], \quad (3c)$$

$$\mathbb{P} \left( C(x^\xi(t_f)) = 0 \right) \geq p. \quad (3d)$$

- 1 Problem formulation
- 2 Modeling improvement**
  - Probability as an expectation
  - Cost refinement
  - Final formulation
- 3 Stochastic Arrow-Hurwicz algorithm
- 4 Numerical results

## Probability as an expectation

$$\text{Let } I(y) = \begin{cases} 1 & \text{if } y = 0, \\ 0 & \text{otherwise.} \end{cases}$$

Then

$$\mathbb{P}\left(C(x^\xi(t_f)) = 0\right) = \mathbb{E}\left(I(\|C(x^\xi(t_f))\|)\right).$$

Thus, Problem (3) can (shortly) be written:

$$\min_{u(\cdot)} \mathbb{E}\left(\min_{v^\xi(\cdot)} K(x^\xi(t_f))\right) \quad (4a)$$

$$\text{s.t. } \mathbb{E}\left(I(\|C(x^\xi(t_f))\|)\right) \geq p. \quad (4b)$$

Formulation (4) opens the possibility to make use of a **stochastic Arrow-Hurwicz algorithm** in order to obtain the solution  $u^\sharp(\cdot)$ .

## Missing the target should not contribute to the cost

Whenever a failure occurred, setting  $v^\xi \equiv 0$  over  $[t_p^\xi + t_d^\xi, t_f]$

- generally makes the satellite miss the target and **does not contribute to the probability constraint**,
- but it forces fuel consumption to its minimum and **contributes to minimize the cost function**.

This yields an **artificially** good expected cost; however, one is not interested in what happens whenever the whole mission has failed.

Therefore, a better formulation is to register only **scenarios** when the target is **effectively hit**; instead of the original expected cost in (4), we thus prefer to deal with a **conditional expected cost**:

$$\mathbb{E} \left( K(x^\xi(t_f)) \mid C(x^\xi(t_f)) = 0 \right) = \frac{\mathbb{E} \left( K(x^\xi(t_f)) \times I(\|C(x^\xi(t_f))\|) \right)}{\mathbb{E} \left( I(\|C(x^\xi(t_f))\|) \right)}$$

## Conditional expected cost

The problem is reformulated as

$$\min_{u(\cdot), v(\cdot)} \frac{\mathbb{E} \left( K(x^\xi(t_f)) \times \mathbb{I}(\|C(x^\xi(t_f))\|) \right)}{\mathbb{E} \left( \mathbb{I}(\|C(x^\xi(t_f))\|) \right)} \quad (5a)$$

$$\text{s.t. } \mathbb{E} \left( \mathbb{I}(\|C(x^\xi(t_f))\|) \right) \geq p. \quad (5b)$$

Such a formulation is however not well-suited for the stochastic Arrow-Hurwicz algorithm:

**a ratio of expectations is not an expectation!**

## An useful lemma

Using compact notation, Problem (5) is:

$$\min_{\mathbf{u}} \frac{J(\mathbf{u})}{\Theta(\mathbf{u})} \quad \text{s.t.} \quad \Theta(\mathbf{u}) \geq p, \quad (6)$$

in which  $J$  and  $\Theta$  assume positive values.

- ① If  $\mathbf{u}^\#$  is a solution of (6) and if  $\Theta(\mathbf{u}^\#) = p$ , then  $\mathbf{u}^\#$  is also a solution of

$$\min_{\mathbf{u}} J(\mathbf{u}) \quad \text{s.t.} \quad \Theta(\mathbf{u}) \geq p. \quad (7)$$

- ② Conversely, if  $\mathbf{u}^\#$  is a solution of (7), and if an optimal Kuhn-Tucker multiplier  $\beta^\#$  satisfies the condition

$$\beta^\# \geq \frac{J(\mathbf{u}^\#)}{\Theta(\mathbf{u}^\#)},$$

then  $\mathbf{u}^\#$  is also a solution of (6).

## Back to a cost in expectation

Finally, instead of (5) we aim at solving

$$\min_{u(\cdot), \mathbf{v}(\cdot)} \mathbb{E} \left( K(x^\xi(t_f)) \times \mathbb{I}(\|C(x^\xi(t_f))\|) \right) \quad (8a)$$

$$\text{s.t. } \mathbb{E} \left( \mathbb{I}(\|C(x^\xi(t_f))\|) \right) \geq p. \quad (8b)$$

The cost function again corresponds to a standard expectation!

## Final formulation and associated Lagrangian

$$\min_{u(\cdot)} \left( \mathbb{E} \left( \min_{v^\xi(\cdot)} K(x^\xi(t_f)) \times I(\|C(x^\xi(t_f))\|) \right) \right)$$

$$\text{s.t. } \mu \rightsquigarrow p - \mathbb{E} \left( I(\|C(x^\xi(t_f))\|) \right) \leq 0.$$

Assuming there exists a saddle point for the associated Lagrangian, we have finally to solve

$$\max_{\mu \geq 0} \min_{u(\cdot)} \left\{ \mu p + \mathbb{E} \left( \min_{v^\xi(\cdot)} (K(x^\xi(t_f)) - \mu) \times I(\|C(x^\xi(t_f))\|) \right) \right\}.$$

**Remark:** it is convenient to put apart the **no-failure event**, namely  $\{t_p \geq t_f\}$  in the problem formulation. For the sake of simplicity, we do not present this last problem improvement. We will denote by  $\pi_f$  the probability of this event.



- 1 Problem formulation
- 2 Modeling improvement
- 3 **Stochastic Arrow-Hurwicz algorithm**
  - Algorithm overview
  - Downstream closed-loop problem
  - Smoothing function I
  - Solving the resulting approximated problem
- 4 Numerical results

# Algorithm overview (1)

In order to solve

$$\max_{\mu \geq 0} \min_{u(\cdot)} \left\{ \mu p + \underbrace{\mathbb{E} \left( \min_{v^\xi(\cdot)} (K(x^\xi(t_f)) - \mu) \times I(\|C(x^\xi(t_f))\|) \right)}_{W(u, \mu, \xi)} \right\}.$$

that is,

$$\max_{\mu \geq 0} \min_{u(\cdot)} \left\{ \mu p + \mathbb{E}(W(u, \mu, \xi)) \right\},$$

we use a **stochastic Arrow-Hurwicz algorithm** (see [2] and [3]).

## Algorithm overview (2)

### Arrow-Hurwicz algorithm

At iteration  $k$ ,

- 1 draw a failure  $\xi^k = (t_p^{\xi^k}, t_d^{\xi^k})$  according to its probability law,
- 2 update  $u(\cdot)$ :

$$u^{k+1} = \Pi_{\mathcal{B}} \left( u^k - \varepsilon^k \nabla_u W(u^k, \mu^k, \xi^k) \right),$$

- 3 update  $\mu$ :

$$\mu^{k+1} = \max \left( 0, \mu^k + \rho^k (\rho + \nabla_\mu W(u^{k+1}, \mu^k, \xi^k)) \right).$$

## Downstream closed-loop problem

Consider the inner optimization problem:

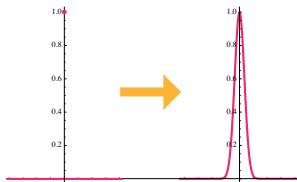
$$W(u, \xi, \mu) = \min_{v^\xi(\cdot)} \left\{ (K(x^\xi(t_f)) - \mu) \times \mathbf{I}(\|C(x^\xi(t_f))\|) \right\},$$

- If reaching the target is **impossible** ( $C(x^\xi(t_f)) \neq 0 \forall v^\xi$ ), the best thing to do is to **stop immediately**:  $W \equiv 0$ .
- If reaching the target is **possible** but **too expensive** (that is  $K(x^\xi(t_f)) \geq \mu$ ), the best thing to do is again to **stop immediately**:  $W \equiv 0$ .
- Therefore, it must be checked that one can reach the target while maintaining fuel consumption below a threshold, and the corresponding optimal control  $v_*^\xi(\cdot)$  must be computed.

At every iteration  $k$ , we must **evaluate** function  $W$  as well as **its derivatives** w.r.t.  $u(\cdot)$  and  $\mu$ . But  $W$  is not differentiable!

## First difficulty: I is not a smooth function

$$I(y) = \begin{cases} 1 & \text{if } y = 0, \\ 0 & \text{otherwise,} \end{cases} \rightsquigarrow I_r(y) = \begin{cases} \left(1 - \frac{y^2}{r^2}\right)^2 & \text{if } y \in [-r, r], \\ 0 & \text{otherwise.} \end{cases}$$



There are specific rules to drive  $r^k$  to 0 as the iteration number  $k$  goes to infinity in order to obtain the best asymptotic **Mean Quadratic Error** of the gradient estimates (see [1]).

## Second difficulty: solving the approximated problem

The approximated closed-loop problem to solve at each iteration is:

$$W_r(u^k, \xi^k, \mu^k) = \min_{v^\xi(\cdot)} \left\{ (K(x^\xi(t_f)) - \mu^k) \times \mathbf{I}_r(\|C(x^\xi(t_f))\|) \right\}.$$

In this setting, we have to check if the target is reached **up to  $r$** .

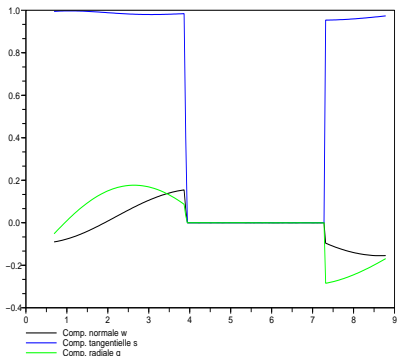
In practice, the solution of the approximated problem is derived from the resolution of two standard optimal control problems.

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- 4 Numerical results**
  - Brief description
  - Results for different values of  $p$
  - The price of safety

## Mission description

### Interplanetary mission (Earth-Mars trajectory):

- duration of the mission: 450 days,
- $\mathbf{t}_p$ : exponential distribution s.t.  $\mathbb{P}(\mathbf{t}_p \geq t_f) = \pi_f \approx 0.58$ ,
- $\mathbf{t}_d$ : exponential distribution s.t.  $\mathbb{P}(2 \leq \mathbf{t}_d \leq 7) \approx 0.80$ .



Using normalized units:

- $t_i = 0.69$  and  $t_f = 8.73$ .

The **deterministic optimal control** has a “bang–off–bang” shape. Along the **deterministic optimal path**, the probability to recover a failure is:

$$p^{\text{det}} \approx 0.94.$$



## Parameters tuning

**Gradient step length:**

$$\varepsilon^k = \frac{a}{b+k} \quad , \quad \rho^k = \frac{c}{d+k} \quad ,$$

↪ usual for a stochastic gradient algorithm.

**Smoothing parameter:**

$$r^k = \frac{\alpha}{\beta + k^{\frac{1}{3}}} \quad ,$$

↪ MQE reduced by a factor 2000 in about 100.000 iterations.

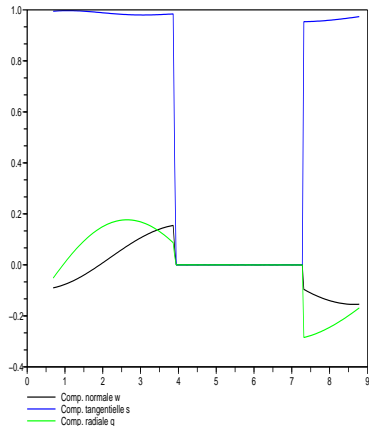
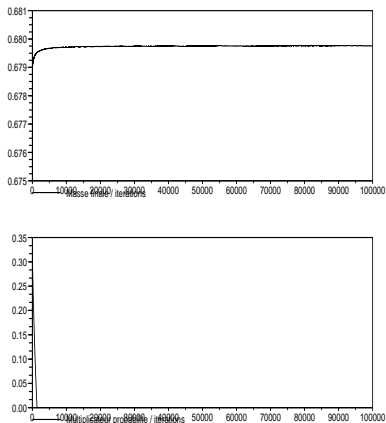


Figure: Probability level  $p < \pi_f$

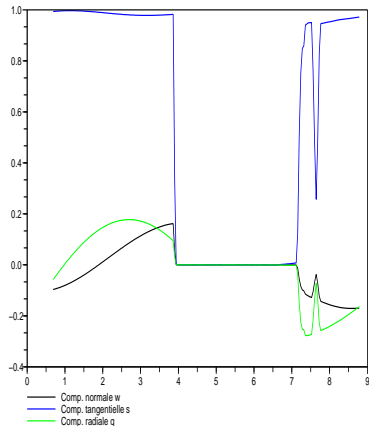
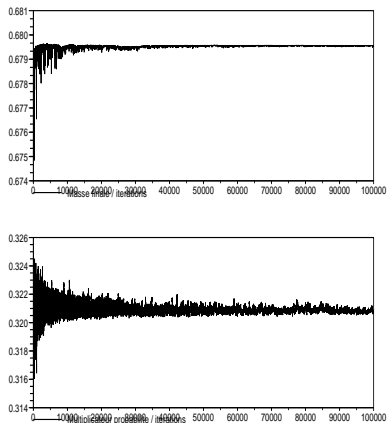


Figure: Probability level  $\rho = 0.750$

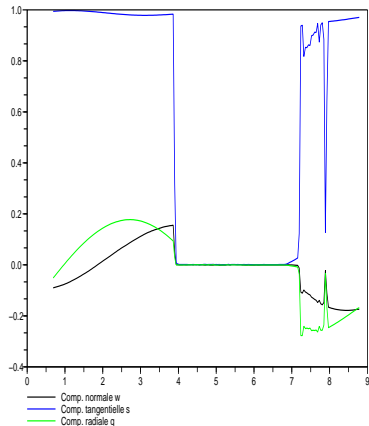
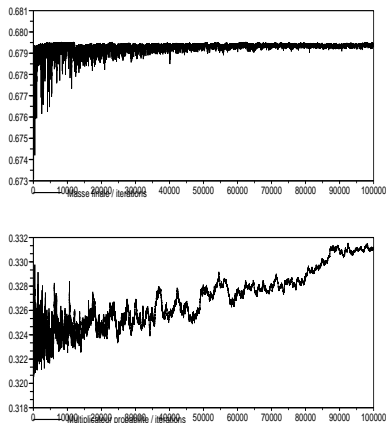


Figure: Probability level  $\rho = 0.960$

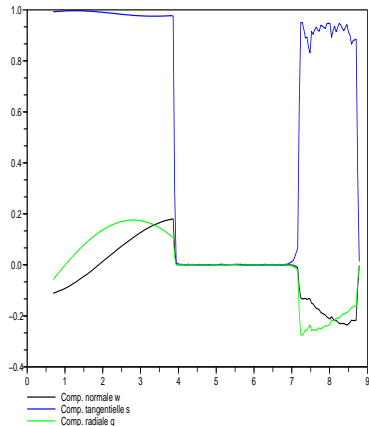
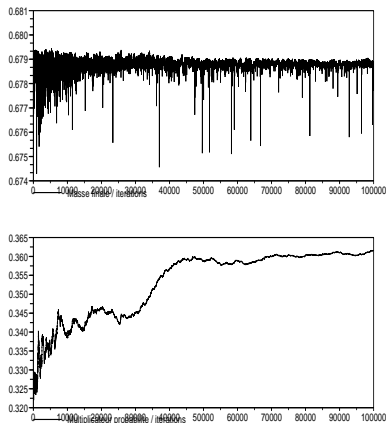
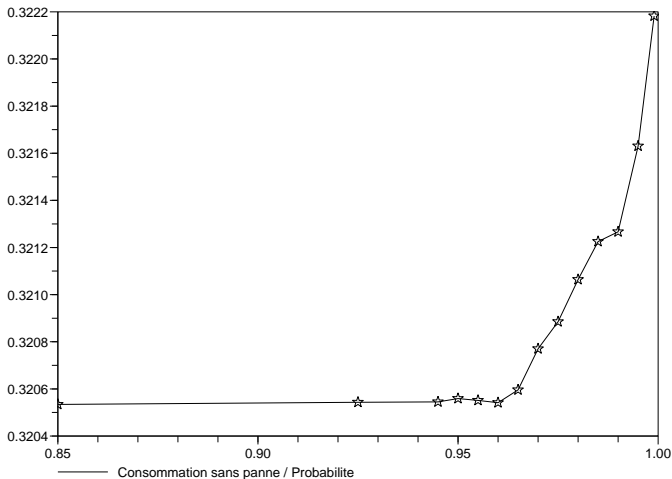


Figure: Probability level  $\rho = 0.990$

# Fuel consumption versus probability level



# Conclusion

## Main conclusion

We are able to deal with probability constraints in the optimal control framework.

## Future works

- *From the theoretical point of view:*
  - existence of a saddle point for the constrained problem,
  - smoothing process (results available only for inequality constraints).
- *From the numerical point of view:*
  - efficient solver for the downstream problem,
  - computer parallelization.



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Thank you for your attention. Any question?

