

Greedy control

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Joint work with E. Zuazua, UAM, Madrid



Outline

- Parameter dependent systems
- Reduced basis methods
- Greedy control
- Numerical examples

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Parameter dependent problems

Real life processes depend on (a huge number of) parameters.

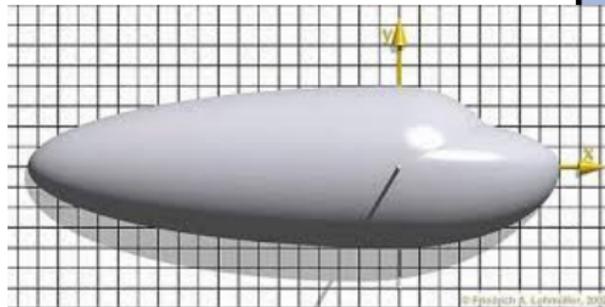
Parameter dependent problems

Real life processes depend on (a huge number of) parameters.

humidity



temperature



curvature

velocity

These parameters are variable, subject to uncertainty, undetermined ...
The study of a parameter dependent problems requires robust approach.

Control of a linear system

Consider the finite dimensional linear control system

$$\begin{cases} x'(t) = Ax(t) & , 0 < t < T, \\ x(0) = x^0. \end{cases} \quad (1)$$

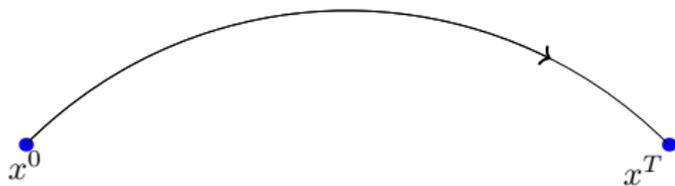
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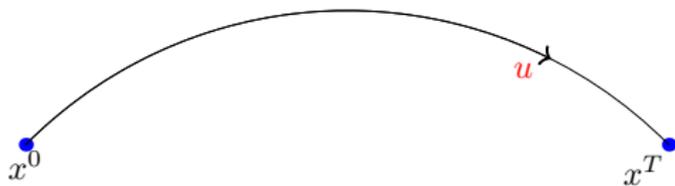


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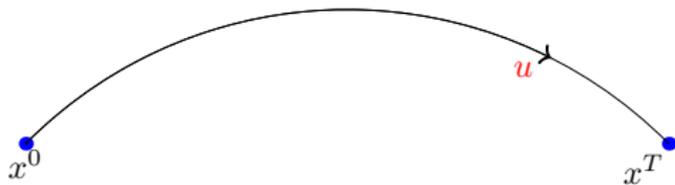


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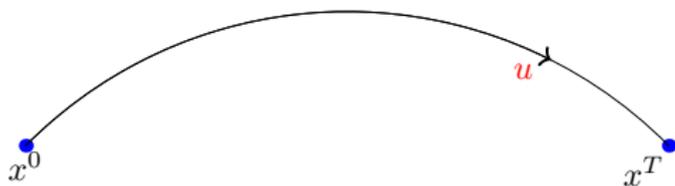


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Controllability

The system (1) is **controllable** in time $T > 0$ if for any initial datum x^0 there exists a control u such that $x(T) = 0$.

The control is not unique in general.

We restrict to a class of a minimal energy norm provided uniqueness.

Control of parameter dependent system

Consider the finite dimensional linear control system

$$\begin{cases} x'(t) = A(\nu)x(t) + B(\nu)u(t), & 0 < t < T, \\ x(0) = x^0. \end{cases}$$

- ▶ $x(t, \nu) = (x_1(t, \nu), \dots, x_N(t, \nu)) \in \mathbb{R}^N$ is the state of the system,
- ▶ $A(\nu)$ is a $N \times N$ -matrix,
- ▶ $B(\nu)$ is a $N \times M$ control operator, $M \leq N$,
- ▶ $u_\nu = u(t, \nu)$ is a M -component control vector in \mathbb{R}^M , $M \leq N$.
- ▶ ν is a multi-parameter living in a compact set \mathcal{N} of \mathbb{R}^d ,

We assume the system is (uniform) controllable for all $\nu \in \mathcal{N}$.
As the dynamics depends on ν , so it does the control u_ν .

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You measure the parameter value, and you determine the control by some standard methods.

And you repeat the process each time for any new value of ν .

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Can we do it better?

The averaged control

- the first attempt to study the control of parameter dependent problems in a systematic manner.

The idea

- to find a parameter independent control such that

$$\int_{\mathcal{N}} x_{\nu}(T, \cdot) d\nu = x^T.$$

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Theorem

(E. Zuazua '14)¹

Averaged controllability holds if and only if the following rank condition is satisfied:

$$\text{rank} \left[B, \int_{\mathcal{N}} [A(\nu)] d\nu B, \int_{\mathcal{N}} [A(\nu)]^2 d\nu B, \dots \right] = N.$$



¹E. ZUAZUA, Averaged Control. *Automatica* **50(12)** (2014) 3077–3087.



M. L. AND E. ZUAZUA, Averaged control and observation of parameter-depending wave equations. *C. R. Acad. Sci. Paris, Ser. I* **352(6)** (2014) 497–502.

From averaged to simultaneous controllability

How far are particular realisation of the system from a desired state?
By applying the averaged control you get

$$\int_{\mathcal{N}} x_{\nu}(T, \cdot) d\nu = x^T.$$

In order to control each component separately you add a **penalty term**.²
Look for the control minimising the functional

$$J_{\kappa}(u) = \frac{1}{2} \|u\|_{L^2}^2 + \underbrace{\kappa \int \|x_{\nu}(T, \cdot) - x^T\|^2 d\nu}_{Penalty}.$$

Letting $\kappa \rightarrow \infty$ you force the particular realisations of the system to be close to 0 as much as possible.



²J. LOHÉAC AND E. ZUAZUA, From averaged to simultaneous controllability ..., preprint 2015.

Greedy control

Fix a control time $T > 0$, an arbitrary initial data x^0 , and a final target $x^T \in \mathbf{R}^N$.

Assumption:

– matrices A_ν, B_ν depend on the parameter in the **Lipschitz manner**.

The controls

$$\nu \in \mathcal{N} \subset \mathbf{R}^d \rightarrow u(t, \nu) \in [L^2(0, T)]^M$$

constitute a manifold $U(\mathcal{N})$ of dimension d in $[L^2(0, T)]^M$.

The idea:

– to determine a finite number of values of ν that yield the best possible approximation of this “control manifold”.

We do not do it in a “naive” way by simply taking a uniform mesh on \mathcal{N} and then evaluating the control for each value ν corresponding to the nodes of this mesh. This would be too expensive.

We look for a distinguished parameter values yielding the **optimal** approximation by the **smallest** number of points.

Each control can be uniquely determined by the relation

$$\mathbf{u}_\nu = \mathbf{B}^* e^{(T-t)\mathbf{A}_\nu^*} \varphi_\nu^0,$$

where $\varphi_\nu^0 \in \mathbf{R}^N$ is the unique minimiser of a quadratic functional associated to the adjoint problem.

This minimiser can be expressed as the solution of the system

$$\mathbf{\Lambda}_\nu \varphi_\nu^0 = \mathbf{x}^T - e^{T\mathbf{A}_\nu} \mathbf{x}^0,$$

where $\mathbf{\Lambda}_\nu$ is the controllability Gramian

$$\mathbf{\Lambda}_\nu = \int_0^T e^{(T-t)\mathbf{A}_\nu} \mathbf{B}_\nu \mathbf{B}_\nu^* e^{(T-t)\mathbf{A}_\nu^*} dt.$$

Greedy control

As we have 1 – 1 correspondence

$$\varphi_\nu^0 \longleftrightarrow u_\nu$$

it is sufficient to get a good approximation of the manifold $\varphi^0(\mathcal{N})$:

$$\nu \in \mathcal{N} \rightarrow \varphi_\nu^0 \in \mathbf{R}^N .$$

Thus our problem can be formulated as:

The greedy control problem

Given $\varepsilon > 0$ determine a *small* family of parameters ν_1, \dots, ν_n in \mathcal{N} so that the corresponding minimisers $\varphi_1^0, \dots, \varphi_n^0$, are such that for every $\nu \in \mathcal{N}$ there exists $\varphi_\nu^{0*} \in \text{span}\{\varphi_1^0, \dots, \varphi_n^0\}$ satisfying

$$\|\varphi_\nu^0 - \varphi_\nu^{0*}\| \leq \varepsilon .$$

Outline

- Parameter dependent systems
- **Reduced basis methods**
- Greedy control
- Numerical examples

In order to achieve this goal we rely on **greedy algorithms** and **reduced bases methods** for parameter dependent PDEs or abstract equations in Banach spaces.



A. COHEN, R. DEVORE, Kolmogorov widths under holomorphic mappings, *IMA Journal on Numerical Analysis*, to appear



A. COHEN, R. DEVORE, Approximation of high-dimensional parametric PDEs, arXiv preprint, 2015.



Y. MADAY, O. MULA, A. T. PATERA, M. YANO, The generalized Empirical Interpolation Method: stability theory on Hilbert spaces with an application to the Stokes equation, submitted

The pure greedy method

X – a Banach space

$K \subset X$ – a compact subset.

The method approximates K by a series of finite dimensional linear spaces V_n (a **linear method**).

The algorithm

The first step

Choose $x_1 \in K$ such that

$$\|x_1\|_X = \max_{x \in K} \|x\|_X.$$

The general step

Having found $x_1 \dots x_n$, denote $V_n = \text{span}\{x_1, \dots, x_n\}$.

Choose the next element

$$x_{n+1} := \arg \max_{x \in K} \text{dist}(x, V_n). \quad (2)$$

The algorithm stops

when $\sigma_n(K) := \max_{x \in K} \text{dist}(x, V_n)$ becomes less than the given tolerance ε .

The greedy idea

The greedy idea

Which one you are going to choose?



Sometimes it is hard to solve the maximisation problem (2).

The weak greedy method

– a relaxed version of the pure one.

The algorithm

Fix a constant $\gamma \in (0, 1]$.

The first step

Choose $x_1 \in K$ such that

$$\|x_1\|_X \geq \gamma \max_{x \in K} \|x\|_X.$$

The general step

Having found $x_1 \dots x_n$, denote $V_n = \text{span}\{x_1, \dots, x_n\}$.

Choose the next element

$$\text{dist}(x_{n+1}, V_n) \geq \gamma \max_{x \in K} \text{dist}(x, V_n). \quad (3)$$

The algorithm stops

when $\sigma_n(K) := \max_{x \in K} \text{dist}(x, V_n)$ becomes less than the given tolerance ε .

Efficiency

In order to estimate **the efficiency of the (weak) greedy algorithm** we compare its approximation rates $\sigma_n(K)$ with the best possible one.

The Kolmogorov n width, $d_n(K)$

– measures how well K can be approximated by a subspace in X of a fixed dimension n .

$$d_n(K) := \inf_{\dim Y=n} \sup_{x \in K} \inf_{y \in Y} \|x - y\|_X.$$

Thus $d_n(K)$ represents optimal approximation performance that can be obtained by a n -dimensional linear space.

The greedy approximation rates have same decay as the Kolmogorov widths.

Theorem

(Cohen, DeVore '15)³

For any $\alpha > 0, C_0 > 0$

$$d_n(K) \leq C_0 n^{-\alpha} \implies \sigma_n(K) \leq C_1 n^{-\alpha}, \quad k \in \mathbf{N},$$

where $C_1 := C_1(\alpha, C_0, \gamma)$.



³A. COHEN, R. DEVORE, Approximation of high-dimensional parametric PDEs, *Acta Numerica*, **24** (2015) 1–159.

Performance obstacles

- ▶ The set K in general consists of infinitely many vectors.
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One uses some **surrogate** value replacing the exact distance appearing in (3) by some uniformly equivalent term.

Practical realisation depends crucially on an existence of an appropriate surrogate .

The vectors chosen by the greedy procedure are the [snapshots](#).

Their computation can be time consuming and computational expensive (**offline part**).



Los Alamos National Laboratory

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Once having chosen the snapshots, one should easily approximate any value $x \in K$ (**online part**).

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Greedy control⁴

Recall

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$$\|\varphi_\nu^0 - \varphi_\nu^{0*}\| \leq \varepsilon.$$

The greedy method choose the next snapshot by maximising

$$\text{dist}_{\nu \in \mathcal{N}}(\varphi_\nu^0, \Phi_n^0),$$

where $\Phi_n^0 = \text{span}\{\varphi_1^0, \dots, \varphi_n^0\}$.

Thus one would have to find φ_ν^0 for every $\nu \in \mathcal{N}$, what is exactly what we want to avoid.

One has to find an appropriate surrogate!



⁴M. L., E. ZUAZUA, Greedy controllability of finite dimensional linear systems, to appear in *Automatica*

Surrogate choice

Suppose we have chosen φ_1^0 . How should we estimate $\text{dist}_{\nu \in \mathcal{N}}(\varphi_\nu^0, \varphi_1^0)$, without knowing φ_ν^0 ?

As

$$\mathbf{\Lambda}_\nu \varphi_\nu^0 = \mathbf{x}^T - e^{T \mathbf{A}_\nu} \mathbf{x}^0, \quad (4)$$

try φ_1^0 as the solution to (4), i.e. compute

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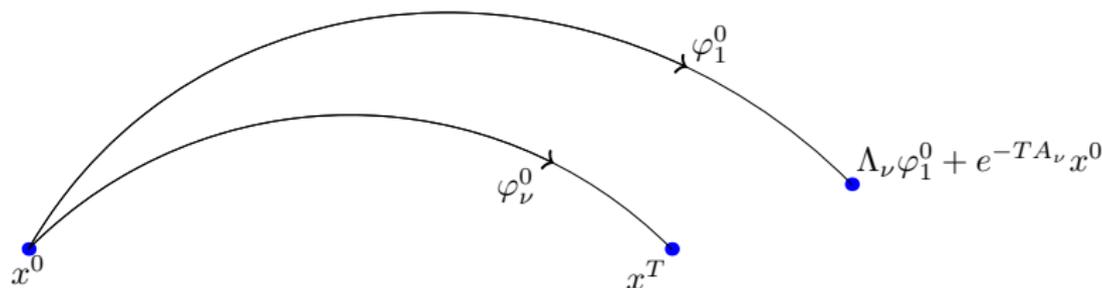
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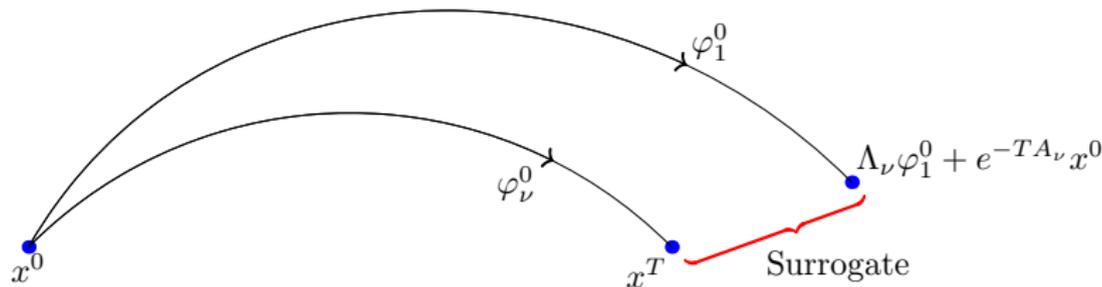
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Surrogate choice

By using the surrogate value

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we **replace** the **unknown** φ_ν^0 by an easy computed term $\mathbf{x}^T - e^{-T\mathbf{A}_\nu} \mathbf{x}^0$.

What about $\mathbf{\Lambda}_\nu \phi_1^0$?

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we **replace** the **unknown** ϕ_ν^0 by an easy computed term $\mathbf{x}^T - e^{-T\mathbf{A}_\nu} \mathbf{x}^0$.

What about $\mathbf{\Lambda}_\nu \phi_1^0$? It represents the value at time T of the solution to our system with the control obtained by solving the corresponding adjoint problem with initial datum ϕ_1^0 .

$$\begin{array}{ccc} & \curvearrowright & \mathbf{u}_\nu^* = \mathbf{B}_\nu^* \phi \\ & & \curvearrowleft \\ \mathbf{1} \uparrow & \begin{array}{l} \phi' - \mathbf{A}_\nu^* \phi = 0 \\ \phi(T) = \phi_1^0 \end{array} & \begin{array}{l} \mathbf{x}(0) = 0 \\ \mathbf{x}' + \mathbf{A}_\nu \mathbf{x} = \mathbf{B}_\nu \mathbf{u}_\nu^* \end{array} \downarrow \mathbf{2} \\ & \implies & \mathbf{\Lambda}_\nu \phi_1^0 = \mathbf{x}(T) \end{array}$$

Construction of the approximating space

Offline part

As the second snapshot, we choose the value for which φ_1^0 gives the worst approximation.

And so on ...

Theorem

The algorithm stops after the most $n_0 \leq N$ steps, and it fulfils the requirements of the weak greedy theory.

Corollary

*Under additional assumption on **analytic dependence** on the parameter, the greedy control algorithm leads to an optimal approximation method. More precisely, for all $\alpha > 0$ there exists $C_\alpha > 0$ such that for any ν the minimiser ϕ_ν^0 can be approximated by linear combinations of the weak-greedy ones as follows:*

$$\text{dist}(\phi_\nu^0; \text{span}\{\phi_j^0 : j = 1, \dots, n\}) \leq C_\alpha n^{-\alpha}.$$

The same applies when \mathcal{N} is infinite-dimensional provided its Kolmogorov width decays polynomially.

Construction of the approximating control for a given parameter value

Online part

Having constructed the approximating space Φ_n^0 how do we construct an approximative control u_ν^* associated to an arbitrary given value $\nu \in \mathcal{N}$. The exact control is given by

$$u_\nu = B_\nu^* e^{-(T-t)\mathbf{A}_\nu^*} \varphi_\nu^0,$$

We construct the approximative one as

$$u_\nu^* = B_\nu^* e^{-(T-t)\mathbf{A}_\nu^*} \sum_i^k \lambda_i \varphi_i^0,$$

where the coefficients λ_i are determined by the projection of the vector $\mathbf{\Lambda}_\nu \phi_\nu^0 = \mathbf{x}^T - e^{-T\mathbf{A}_\nu} \mathbf{x}^0$ to the space $\mathbf{\Lambda}_\nu \Phi_n^0 = \text{span}\{\mathbf{\Lambda}_\nu \varphi_1^0, \dots, \mathbf{\Lambda}_\nu \varphi_n^0\}$.

N.B.

$$u_\nu^* \notin \text{span}\{u_1, \dots, u_n\}$$

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The first example

We consider the system

$$\begin{cases} x'(t) = \mathbf{A}(\nu)x(t) + Bu(t), & 0 < t < T, \\ x(0) = x^0. \end{cases}$$

where

$$\mathbf{A} = \begin{pmatrix} \mathbf{0} & -I \\ \nu(N/2 + 1)^2 \tilde{\mathbf{A}} & \mathbf{0} \end{pmatrix},$$

$$\tilde{\mathbf{A}} = \begin{pmatrix} 2 & -1 & 0 & \cdots & 0 & 0 \\ -1 & 2 & -1 & \cdots & 0 & 0 \\ 0 & -1 & 2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 2 & -1 \\ 0 & 0 & 0 & \cdots & -1 & 2 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ (N/2 + 1)^2 \end{pmatrix}.$$

The system corresponds to the discretisation of the wave equation problem with the control on the right boundary:

$$\begin{cases} \partial_{tt}v - \nu \partial_{xx}v = 0, & (t, x) \in \langle 0, T \rangle \times \langle 0, 1 \rangle \\ v(t, 0) = 0, & v(t, 1) = u(t) \\ v(0, x) = v_0, & \partial_t v(x, 0) = v_1. \end{cases}$$

We take the following values:

$$T = 3, N = 20$$

$$v_0 = \sin(\pi x), v_1 = 0$$

$$x^T = 0$$

and we assume

$$\nu \in [1, 10] = \mathcal{N}$$

The system satisfies the Kalman's rank condition for any ν .

The greedy control has been applied with $\varepsilon = 0.5$ and the uniform discretisation of \mathcal{N} in $k = 100$ values.

The offline algorithm stopped after 10 iterations.

The control manifold in \mathbf{R}^{20} is well approximated by a 10-D subspace.

10 values (out of 100) were chosen in the following order:

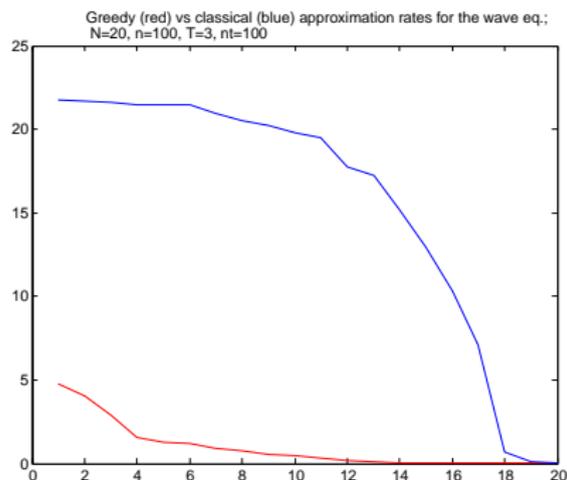
10.00 2.44 6.58 8.65 9.28 1.54 1.00 7.84 3.43 1.36

The corresponding minimisers have been calculated and saved.

The online part should us give an approximative control for any $\nu \in [1, 10]$.

Let us try!

The efficiency of the method



Blue curve represent approximation rates obtained by choosing minimisers in a *naive* way:
just by taking vectors of the canonical basis.

The greedy does much better!

The heat equation

For

$$\mathbf{A} = \nu(N+1)^2 \begin{pmatrix} 2 & -1 & 0 & \cdots & 0 & 0 \\ -1 & 2 & -1 & \cdots & 0 & 0 \\ 0 & -1 & 2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 2 & -1 \\ 0 & 0 & 0 & \cdots & -1 & 2 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ (N+1)^2 \end{pmatrix},$$

the system corresponds to the discretisation of the heat equation problem with the control on the right boundary:

$$\begin{cases} \partial_t v - \nu \partial_{xx} v = 0, & (t, x) \in \langle 0, T \rangle \times \langle 0, 1 \rangle \\ v(t, 0) = 0, & v(t, 1) = u(t) \\ v(0, x) = v_0, . \end{cases}$$

Results

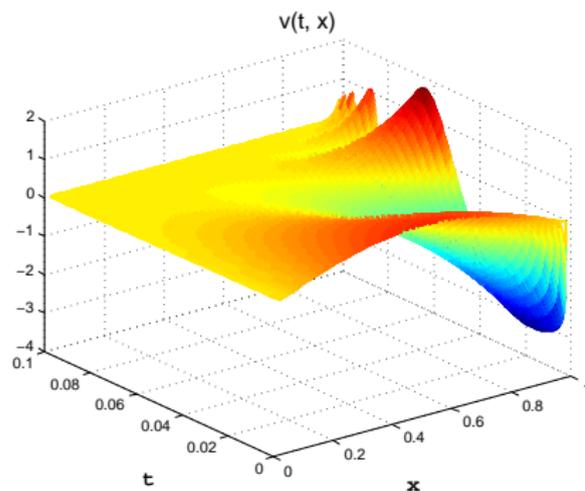
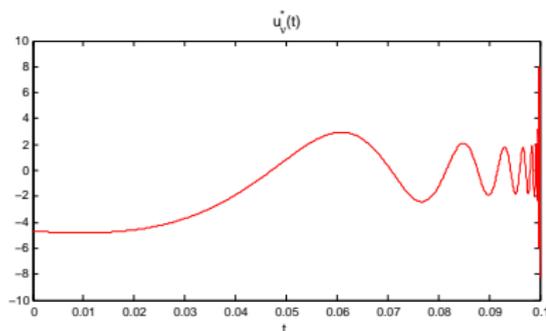
The greedy is applied with

$$T = 0.1, \quad \varepsilon = 0.0001, \quad \nu \in [1, 2] = \mathcal{N}$$

The algorithm stops after only 3 iterations, choosing 3 (out of 100) parameter values in the following order:

1.00 1.18 1.45.

We present the result for $\nu = \sqrt{2}$.



Open problems and perspectives

- ▶ Our work can be extended to systems with the target state and/or initial conditions depending on the parameter as well.
- ▶ Alternative surrogates need to be found so to make the recursive choice process of the various ν 's (offline part) faster and cheaper. Of special interest is the affine dependence case

$$\mathbf{B}(\nu) = \bar{\mathbf{B}} + \sum_j \nu_j \mathbf{B}_j$$

with $(\|\mathbf{B}_j\|) \in l^p$ for some $p \leq 1$ which should significantly reduce the computational cost.

- ▶ Our work can be extended to PDE but analyticity of controls with respect to parameters has to be ensured. This typically holds for elliptic and parabolic equations. But not for wave-like equations. Indeed, solutions of

$$y_{tt} - \nu^2 y_{xx} = 0$$

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Thanks for your attention!