Latent Force Models: Combining Data Driven and Mechanistic Modelling Paradigms

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Rank Prize Workshop

28th March 2012

Outline

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Styles of Machine Learning

Background: interpolation is easy, extrapolation is hard

- Urs Hölzle keynote talk at NIPS 2005.
  - Emphasis on massive data sets.
  - Let the data do the work—more data, less extrapolation.
- Alternative paradigm:
  - Very scarce data: computational biology, human motion.
  - How to generalize from scarce data?
  - Need to include more assumptions about the data (e.g. invariances).

General Approach

Broadly Speaking: Two approaches to modeling

data modeling | *mechanistic modeling*

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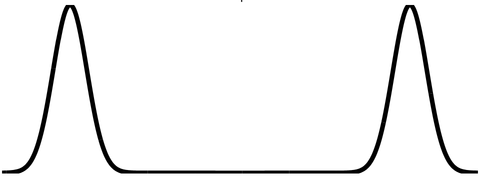

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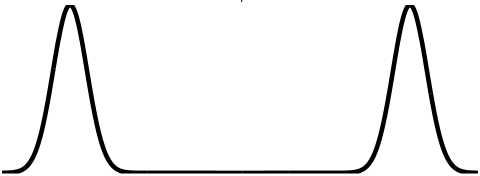

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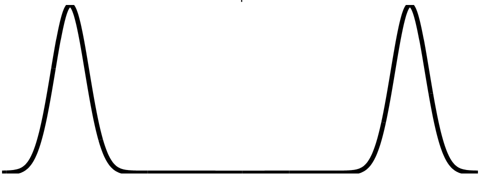
mechanistic modeling

impose physical laws

knowledge driven



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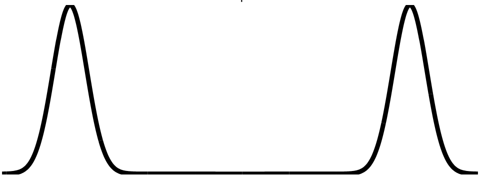

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differential equations

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Weakly Mechanistic

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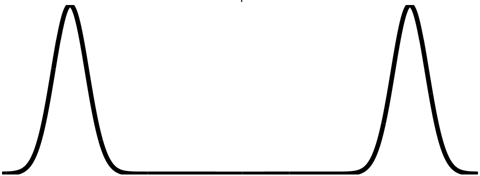


Weakly Mechanistic vs Strongly Mechanistic

- Underlying data modeling techniques there are *weakly mechanistic* principles (e.g. smoothness).
- In physics the models are typically *strongly mechanistic*.
- In principle we expect a range of models which vary in the strength of their mechanistic assumptions.
- This work is one part of that spectrum: add further mechanistic ideas to weakly mechanistic models.

Dimensionality Reduction

- Linear relationship between the data, $\mathbf{X} \in \Re^{n\times p}$, and a reduced dimensional representation, $\mathbf{F} \in \Re^{n\times q}$, where $q \ll p$.

$$\mathbf{X} = \mathbf{F}\mathbf{W} + \boldsymbol{\epsilon},$$

$$\boldsymbol{\epsilon} \sim \mathcal{N}\left(\mathbf{0}, \boldsymbol{\Sigma}\right)$$

- Integrate out $\mathbf{F}$, optimize with respect to $\mathbf{W}$.
- For Gaussian prior, $\mathbf{F} \sim \mathcal{N}\left(\mathbf{0}, \mathbf{I}\right)$
    - and $\Sigma = \sigma^2\mathbf{I}$ we have probabilistic PCA (Tipping and Bishop, 1999; Roweis, 1998).
    - and Σ constrained to be diagonal, we have factor analysis.

Dimensionality Reduction: Temporal Data

- Deal with temporal data with a temporal latent prior.
- Independent Gauss-Markov priors over each $f_i(t)$ leads to : Rauch-Tung-Striebel (RTS) smoother (Kalman filter).
- More generally consider a Gaussian process (GP) prior,

$$p\left(\mathbf{F}|\mathbf{t}\right) = \prod_{i=1}^{q} \mathcal{N}\left(\mathbf{f}_{:,i}|\mathbf{0}, \mathbf{K}_{f_{:,i},f_{:,i}}\right).$$

Joint Gaussian Process

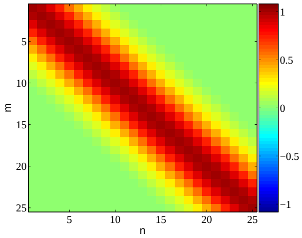
- Given the covariance functions for $\{f_i(t)\}$ we have an implied covariance function across all $\{x_i(t)\}$—(ML: semi-parametric latent factor model (Teh et al., 2005), Geostatistics: linear model of coregionalization).
- Rauch-Tung-Striebel smoother has been preferred
  - linear computational complexity in n.
  - Advances in sparse approximations have made the general GP framework practical. (Titsias, 2009; Snelson and Ghahramani, 2006; Quiñonero Candela and Rasmussen, 2005).

Gaussian Process: Exponentiated Quadratic Covariance

- Take, for example, exponentiated quadratic form for covariance.

$$k\left(t, t'\right) = \alpha \exp\left(-\frac{\left|\left|t - t'\right|\right|^2}{2\ell^2}\right)$$

- Gaussian process over latent functions.



Mechanical Analogy

Back to Mechanistic Models!

- These models rely on the latent variables to provide the dynamic information.
- We now introduce a further dynamical system with a *mechanistic* inspiration.
- Physical Interpretation:
  - the latent functions, $f_i(t)$ are q forces.
  - We observe the displacement of p springs to the forces.,
  - Interpret system as the force balance equation, $\mathbf{XD} = \mathbf{FS} + \boldsymbol{\epsilon}$.
  - Forces act, e.g. through levers — a matrix of sensitivities, $\mathbf{S} \in \Re^{q \times p}$.
  - Diagonal matrix of spring constants, $\mathbf{D} \in \Re^{p \times p}$.
  - Original System: $\mathbf{W} = \mathbf{SD}^{-1}$.

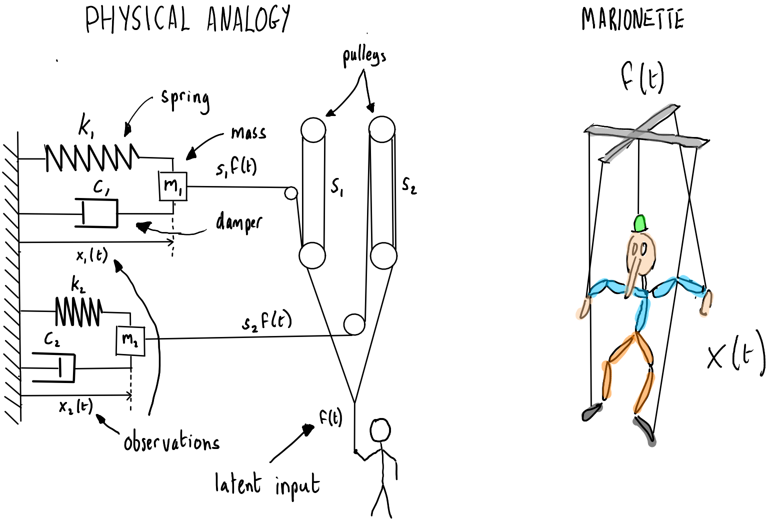
Extend Model

- Add a damper and give the system mass.

$$\mathbf{F}\mathbf{S} = \ddot{\mathbf{X}}\mathbf{M} + \dot{\mathbf{X}}\mathbf{C} + \mathbf{X}\mathbf{D} + \epsilon.$$

- Now have a second order mechanical system.
- It will exhibit inertia and resonance.
- There are many systems that can also be represented by differential equations.
  - When being forced by latent function(s), $\{f_i(t)\}_{i=1}^q$, we call this a *latent force model*.

Physical Analogy



- For Gaussian process we can compute the covariance matrices for the output displacements.
- For one displacement the model is

$$m_k \ddot{x}_k(t) + c_k \dot{x}_k(t) + d_k x_k(t) = b_k + \sum_{i=0}^{q} s_{ik} f_i(t), \qquad (1)$$

  where, m_k is the kth diagonal element from $\mathbf{M}$ and similarly for c_k and d_k. s_{ik} is the i, kth element of $\mathbf{S}$.
- Model the latent forces as q independent, GPs with exponentiated quadratic covariances

$$k_{f_i f_l}(t, t') = \exp\left(-\frac{(t - t')^2}{2\ell_i^2}\right) \delta_{il}.$$

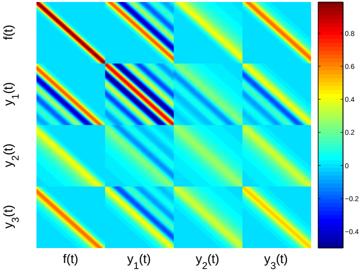
Covariance for ODE Model

- Exponentiated Quadratic Covariance function for $f(t)$

$$x_j(t) = \frac{1}{m_j\omega_j} \sum_{i=1}^{q} s_{ji} \exp(-\alpha_j t) \int_0^t f_i(\tau) \exp(\alpha_j \tau) \sin(\omega_j (t-\tau)) \mathrm{d}\tau$$

- Joint distribution for $x_1(t)$, $x_2(t)$, $x_3(t)$ and $f(t)$. Damping ratios:

ζ_1	ζ_2	ζ_3
0.125	2	1



Covariance for ODE Model

- Analogy

$$x = \sum_i \mathbf{e}_i^\top \mathbf{f}_i \quad \mathbf{f}_i \sim \mathcal{N}(\mathbf{0}, \Sigma_i) \rightarrow x \sim \mathcal{N}\left(0, \sum_i \mathbf{e}_i^\top \Sigma_i \mathbf{e}_i\right)$$

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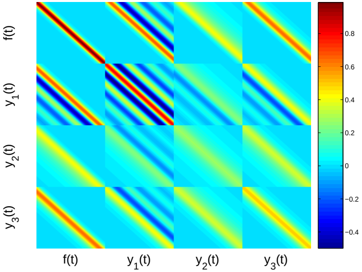

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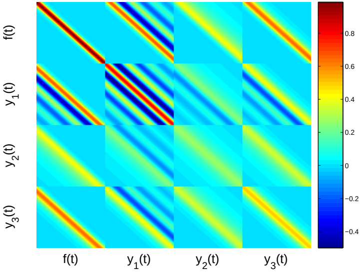

Joint Sampling of $x(t)$ and $f(t)$

- `lfmSample`

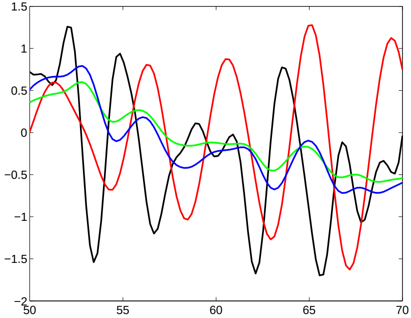

Figure: Joint samples from the ODE covariance, *black*: $f(t)$, *red*: $x_1(t)$ (underdamped), *green*: $x_2(t)$ (overdamped), and *blue*: $x_3(t)$ (critically damped).

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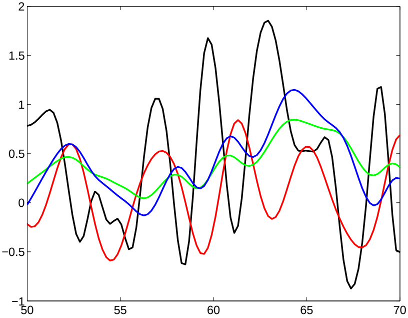

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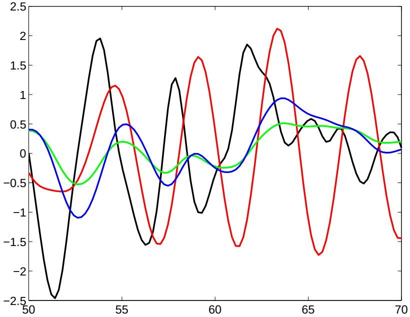

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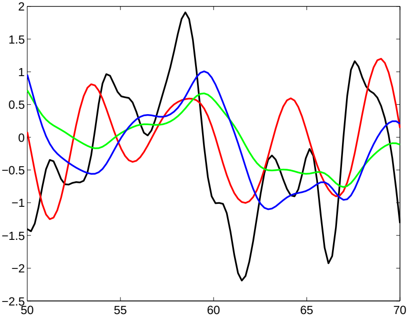

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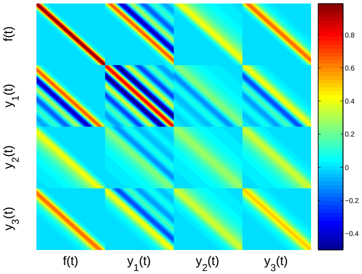

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Example: Motion Capture

Mauricio Alvarez and David Luengo (Álvarez et al., 2009, 2011a)

- Motion capture data: used for animating human motion.
- Multivariate time series of angles representing joint positions.
- Objective: generalize from training data to realistic motions.
- Use 2nd Order Latent Force Model with mass/spring/damper (resistor inductor capacitor) at each joint.

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Prediction of Test Motion

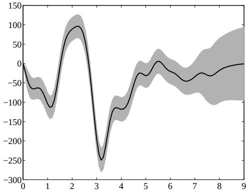
- Model left arm only.
- 3 balancing motions (18, 19, 20) from subject 49.
- 18 and 19 are similar, 20 contains more dramatic movements.
- Train on 18 and 19 and testing on 20
- Data was down-sampled by 32 (from 120 fps).
- Reconstruct motion of left arm for 20 given other movements.
- Compare with GP that predicts left arm angles given other body angles.

Mocap Results

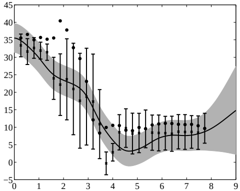
Table: Root mean squared (RMS) angle error for prediction of the left arm's configuration in the motion capture data. Prediction with the latent force model outperforms the prediction with regression for all apart from the radius's angle.

Angle	Latent Force Error	Regression Error
Radius	4.11	4.02
Wrist	6.55	6.65
Hand X rotation	1.82	3.21
Hand Z rotation	2.76	6.14
Thumb X rotation	1.77	3.10
Thumb Z rotation	2.73	6.09

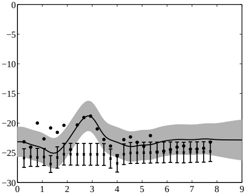
Mocap Results II



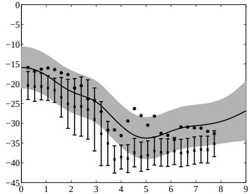
(a) Inferred Latent Force



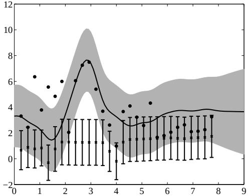
(b) Wrist



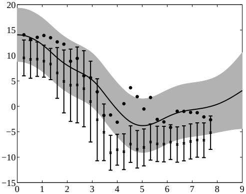
(c) Hand X Rotation



(d) Hand Z Rotation



(e) Thumb X Rotation



(f) Thumb Z Rotation

Figure: Predictions from LFM (solid line, grey error bars) and direct regression (crosses with stick error bars).

Motion Capture Experiments

- Data set is from the CMU motion capture data base[1].
- Two different types of movements: golf-swing and walking.
- Train on a subset of motions for each movement and test on a different subset.
- This assesses the model's ability to extrapolate.
- For testing: condition on three angles associated to the root nodes and first five and last five frames of the motion.
- Golf-swing use leave one out cross validation on four motions.
- For the walking train on 4 motions and validate on 8 motions.

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[1]The CMU Graphics Lab Motion Capture Database was created with funding from NSF EIA-0196217 and is available at `http://mocap.cs.cmu.edu`.

Motion Capture Results

Table: RMSE and R^2 (explained variance) for golf swing and walking

Movement	**Method**	**RMSE**	**R^2 (%)**
Golf swing	IND GP	21.55 ± 2.35	30.99 ± 9.67
	MTGP	21.19 ± 2.18	45.59 ± 7.86
	SLFM	21.52 ± 1.93	49.32 ± 3.03
	LFM	$\mathbf{18.09 \pm 1.30}$	$\mathbf{72.25 \pm 3.08}$
Walking	IND GP	8.03 ± 2.55	30.55 ± 10.64
	MTGP	7.75 ± 2.05	37.77 ± 4.53
	SLFM	7.81 ± 2.00	36.84 ± 4.26
	LFM	$\mathbf{7.23 \pm 2.18}$	$\mathbf{48.15 \pm 5.66}$

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