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Time and State Dependent Neural Delay Differential Equations

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Motivation

- ➔ Discontinuities and delayed terms are encountered in many domains (physics, engineering, medicine, economics, etc...).
- ➔ These systems cannot be modelled and simulated with ODEs.
- ➔ Latent variables are introduced to solve this issue which lack physical interpretability.
- ➔ Delay Differential Equations (DDEs) naturally appear as good candidates for such systems.

We revisit the recently proposed Neural DDE by introducing **Neural State-Dependent DDE (SDDDE)**, a general and flexible framework that can model multiple and state- and time-dependent delays.

Modelling choice

Neural ODE

$$\frac{dy(t)}{dt} = \mathbf{f}_\theta(t, \mathbf{y}(t)), \quad \mathbf{y}(0) = \mathbf{y}_0.$$

ANODE

$$\frac{d}{dt} \begin{bmatrix} \mathbf{y}(t) \\ \mathbf{a}(t) \end{bmatrix} = \mathbf{f}_\theta \left(t, \begin{bmatrix} \mathbf{y}(t) \\ \mathbf{a}(t) \end{bmatrix} \right), \quad \begin{bmatrix} \mathbf{y}(0) \\ \mathbf{a}(0) \end{bmatrix} = \begin{bmatrix} \mathbf{y}_0 \\ \mathbf{0} \end{bmatrix}.$$

Neural DDE

$$\frac{dy(t)}{dt} = \mathbf{f}_\theta(t, \mathbf{y}(t), \mathbf{y}(t - \tau)), \quad \tau \in \mathbb{R}^+$$

$$\mathbf{y}(t < 0) = \phi(t),$$

Neural Laplace

$$\mathbf{p} = \mathbf{h}_\gamma((\mathbf{y}(t_1), t_1), \dots, (\mathbf{y}(t_T), t_T))$$

$$\mathbf{F}(\mathbf{s}) = v(\mathbf{g}_\beta(\mathbf{p}, u(\mathbf{s})))$$

Neural SDDDE

$$\frac{dy(t)}{dt} = \mathbf{f}_\theta(t, \mathbf{y}(t), \mathbf{y}(t - \tau_1(t, \mathbf{y}(t))), \dots, \mathbf{y}(t - \tau_k(t, \mathbf{y}(t))))$$

$$\mathbf{y}(t < 0) = \phi(t)$$

Our method can handle :

- ➔ multiple delays
- ➔ constant, state and time dependent delays

It cannot handle delays defined through integrals as typically found in integro-differential equations.

Delay types	τ 's Definition	Neural DDE	NPCDDEs	Neural Laplace	Neural SDDDE
References	-	[1]	[2]	[3]	This work
Constant	$\tau = a$	✓	×	✓	✓
Piece-wise constant	$\tau = \lfloor \frac{t-a}{a} \rfloor a$	×	✓	✓	✓
Time-dependent	$\tau = g(t)$	×	×	✓	✓
State-dependent	$\tau = g(t, y(t))$	×	×	×	✓
Continuous	$\tau = \int_0^t g(s, y(s)) ds$	×	×	×	×

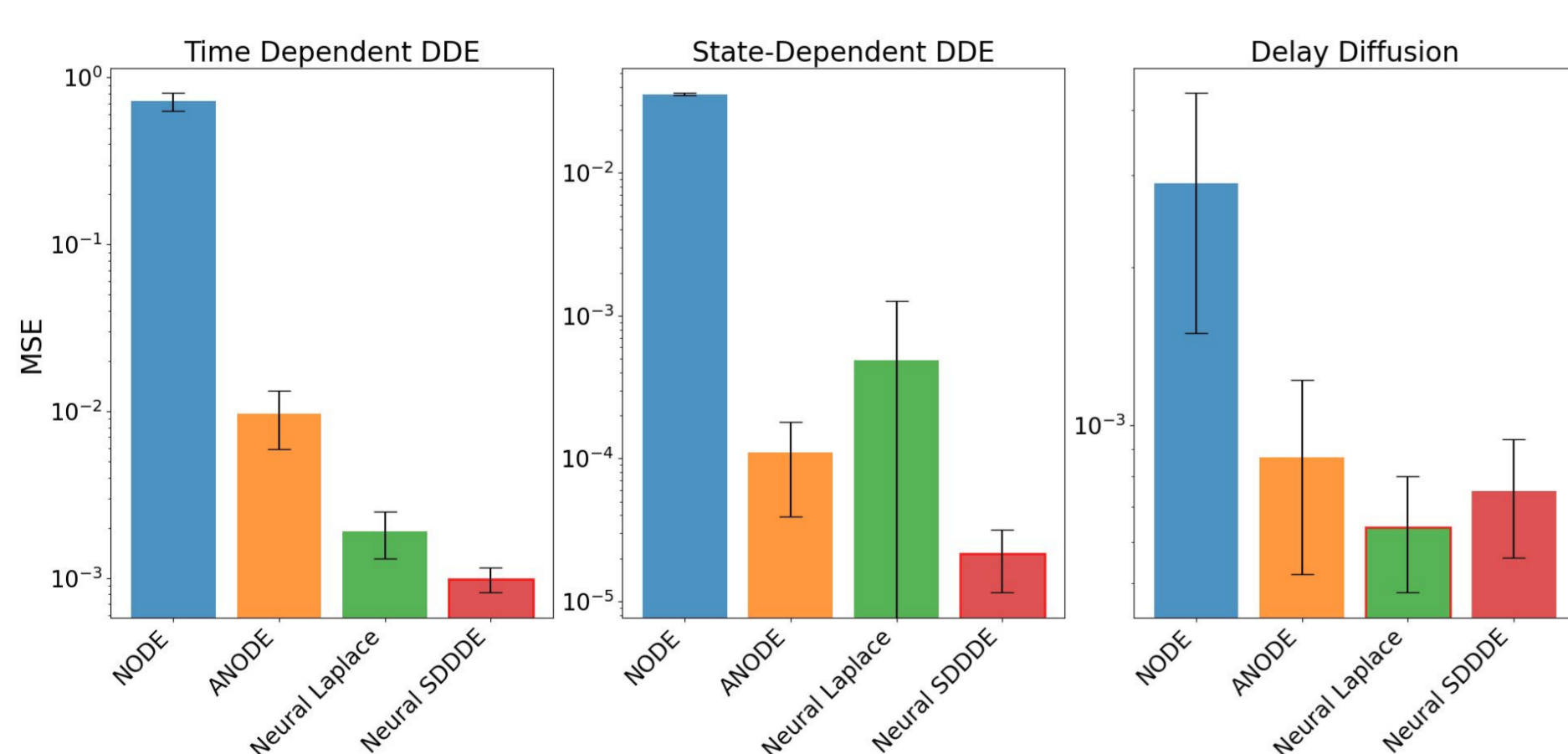
Experiments & Results

Time Dependent DDE

$$\tau(t) = 2 + \sin(t)$$

$$\frac{dy(t)}{dt} = y(t)[1 - y(t - \tau(t))],$$

Test dataset

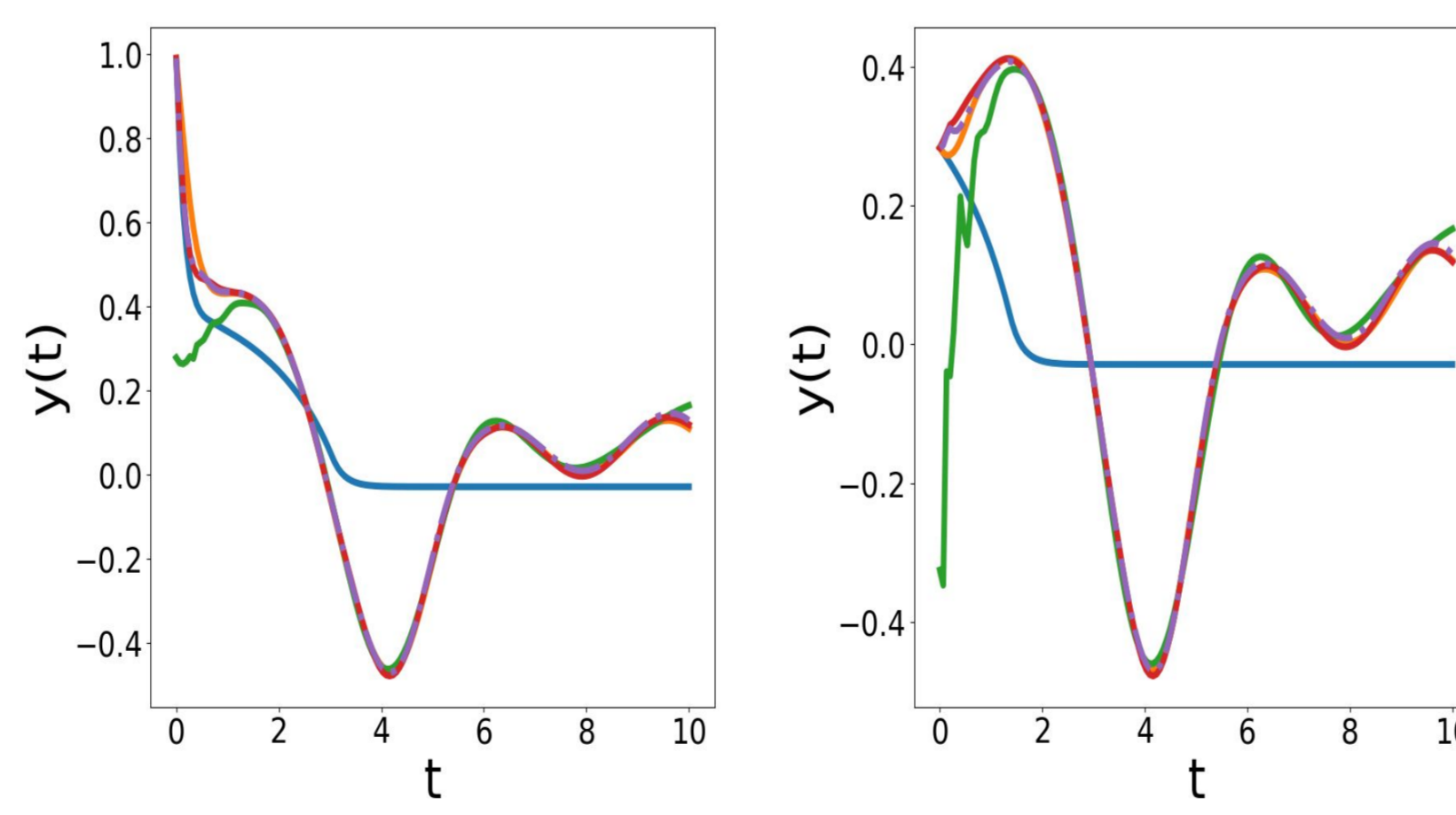


State Dependent DDE

$$\tau(y) = \frac{1}{2} \cos(y(t))$$

$$\frac{dy(t)}{dt} = -\alpha(t)y(t) + \beta(t) \frac{y^2(t - \tau(y))}{1 + y^2(t - \tau(y))} + \gamma(t)$$

Changing history function dataset



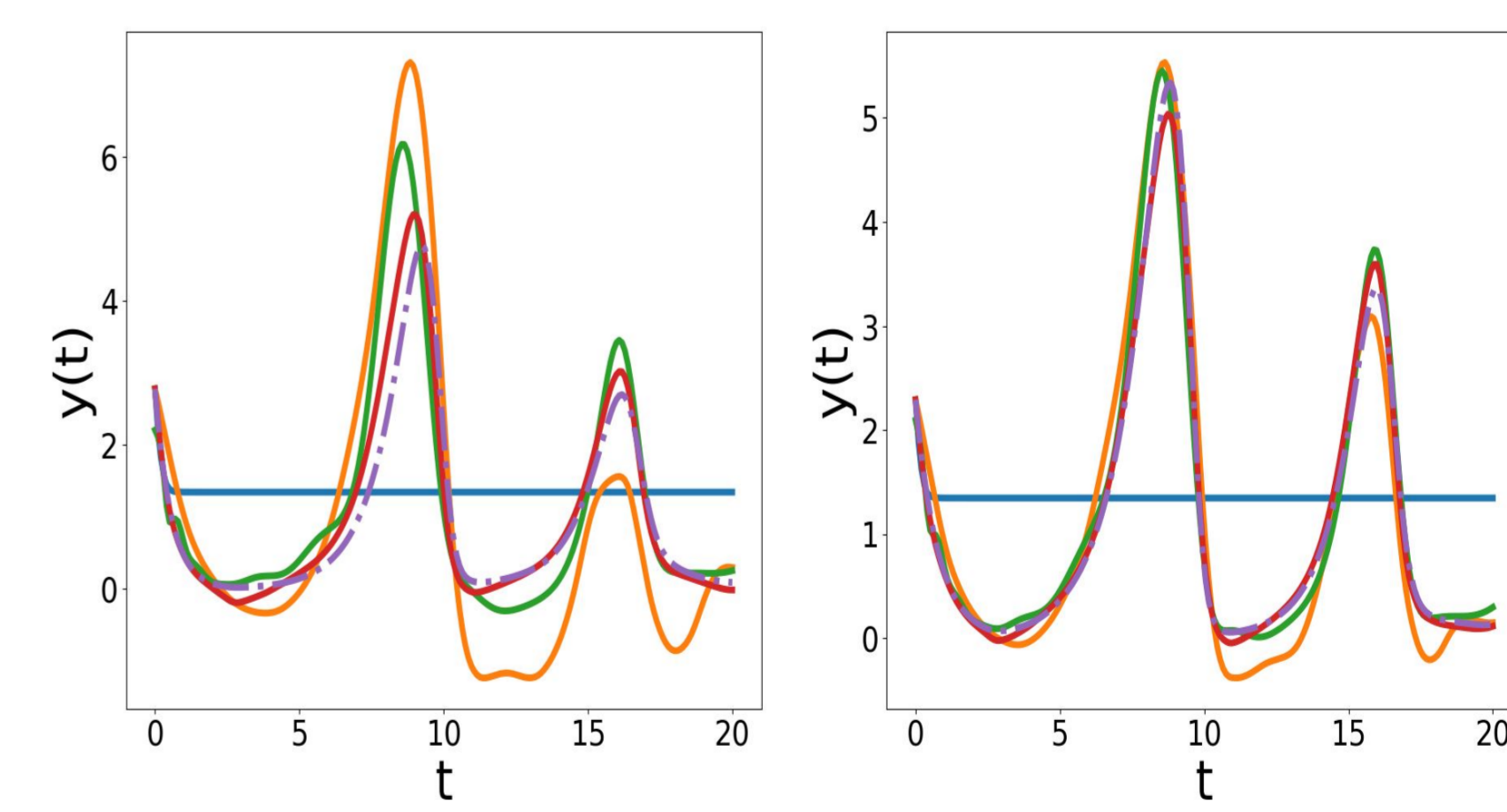
State dependent sample with new history function

Delay Diffusion

$$\tau = 2$$

$$\frac{\partial u}{\partial t}(x, t) = D \frac{\partial^2 u}{\partial x^2}(x, t) + ru(x, t)(1 - u(x, t - \tau)),$$

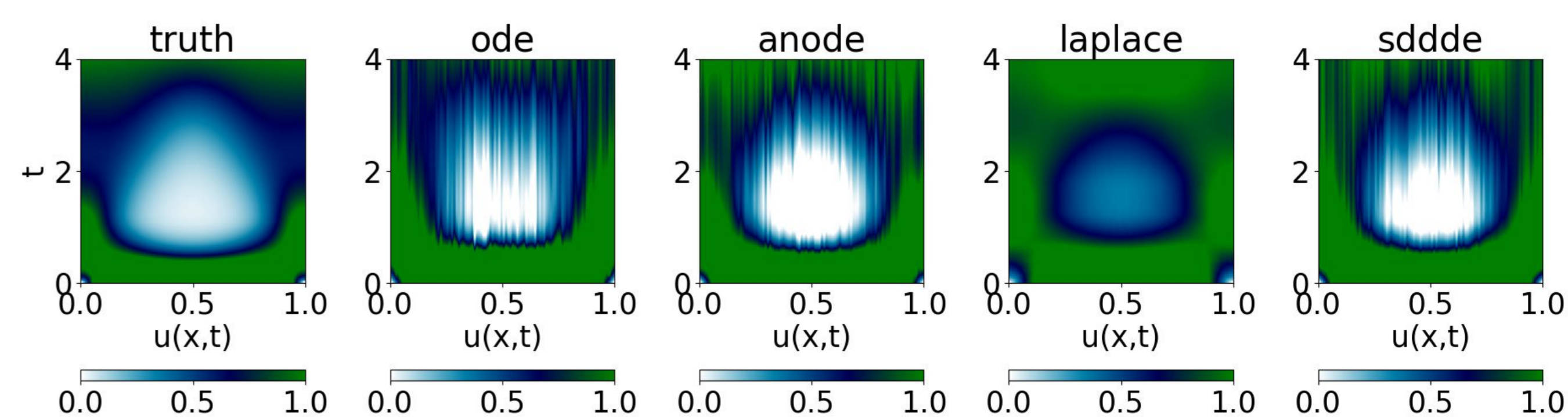
Out of distribution (OOD) dataset



Time dependent OOD sample

Conclusion

- ➔ More experiments and discussions are in the paper !
- ➔ Neural SDDDE almost consistently outperforms all other models.
- ➔ With the OOD and changing history function dataset, we show SDDDE's robustness.



Delay Diffusion OOD sample