



TREND
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A Continuously Tunable Time-Delayed Nonlinear Feedback System

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ELECTRONICS
& APPLIED PHYSICS

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Introduction

Time-delayed nonlinear feedback systems can:

- Produce rich varieties of chaotic behavior
- Synchronize and communicate privately when coupled (if they have similar parameters)

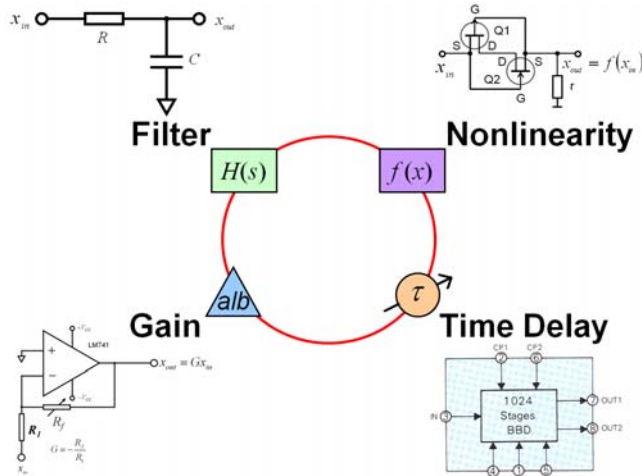
New developments in these systems could lead to new sensor and communication platforms.

Mackey-Glass Equation

$$\frac{dx(t)}{dt} = \frac{ax(t-\tau)}{1+x^{10}(t-\tau)} - bx(t)$$

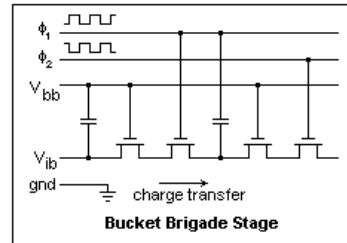
- Originally developed to model physiological systems [Mackey, M. C. and Glass, L., *Science* **197** (1977), pp. 287-289]
- Can produce steady state, periodic, and chaotic behaviors
- Simple electronic analog available [Namajūnas et al., *Phys. Lett. A* **201** (1995), pp. 42-46.]

Mackey-Glass System



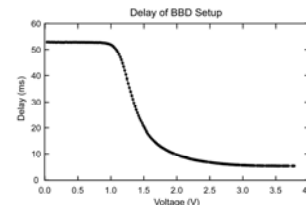
Bucket Brigade Device

- Controlled by driving frequency (generated by a Voltage-Controlled Oscillator)
- Produces a continuously tunable time delay
- Analog in amplitude, discrete in time
- Moves charge from a capacitor to the next at each clock cycle



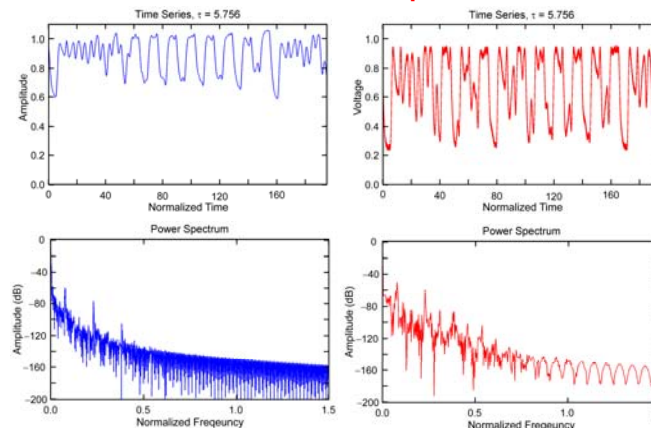
Experimental BBD Data

- 512 capacitor pairs
- Driving frequencies of 10-100 kHz
- Time delays of 5.1-52.7 ms



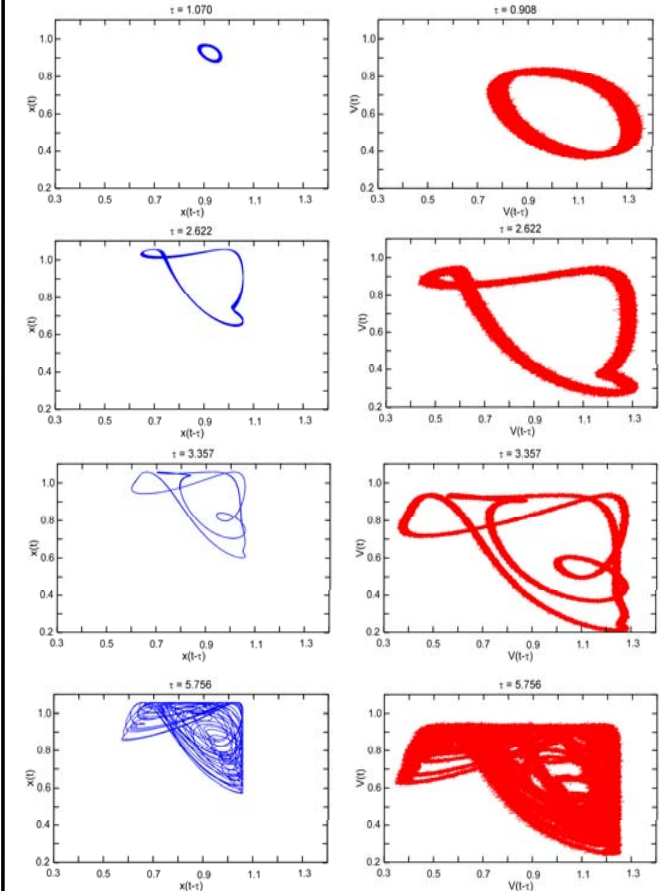
Mackey-Glass System Results

Simulation vs. Experiment



Time Delay Embeddings

Simulation vs. Experiment



Main Conclusions and Future Work

- Demonstrated operation of electrically tunable time delay for nonlinear dynamical systems
- Excellent correspondence with simulations of Mackey-Glass numerical model
- Create an experimental τ -bifurcation diagram
- Explore coupled systems with different time delays
- Investigate adaptive schemes that maintain synchronization with time-varying time delay