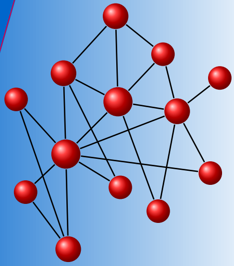
4DM50: Dynamics and Control of Cooperation

Synchronization experiments



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TU/e Technische Universiteit Eindhoven University of Technology

Outline

Recap

Experimental setup

Performing experiments

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Diffusively coupled systems

- Systems of the form

$$\begin{cases} \dot{x}_i = f(x_i) + Bu_i \\ y_i = Cx_i \end{cases}$$

with $CB > 0$

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- System dynamics in new coordinates

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- Assumption 1: systems are strictly semi-passive
- Assumption 2: subsystem $\dot{z}_i = q(z_i, y_i)$ is exponentially convergent w.r.t. input y_i

- Strict semi-passivity: there exists $S : \mathbb{R}^n \to \mathbb{R}_+$ such that the dissipation inequality
$$\dot{S} \leq y_i^T u_i$$
is strict for all x_i outside some ball $\mathcal{B} \subset \mathbb{R}^n$

Intermezzo

- Strict semi-passivity: there exists $S : \mathbb{R}^n \to \mathbb{R}_+$ such that the dissipation inequality

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- Condition for exponential convergence of subsystem $\dot{z}_i = q(z_i, y_i)$ is w.r.t. input y_i:

  There exists a $(n-m) \times (n-m)$ matrix $P = P^T > 0$ such that the eigenvalues of

$$P\left(\frac{\partial q}{\partial z}(z, w)\right) + \left(\frac{\partial q}{\partial z}(z, w)\right)^T P$$

  are negative and separated away from zero for all $(z, w) \in \mathbb{R}^{n-m} \times \mathcal{W}$

Networks of systems with time-delayed interaction:

$$u_i(t) = \sigma \sum_{j \in \mathcal{N}_i} a_{ij}(y_j(t-\tau) - y_i(t-\tau))$$

with $a_{ij} = a_{ji} > 0$ and $j \in \mathcal{N}_i \Leftrightarrow i \in \mathcal{N}_j$

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Synchronization of time-delay coupled systems

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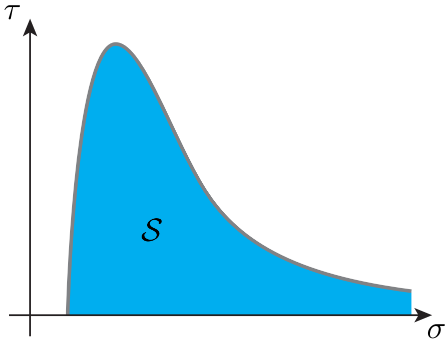

Coupling matrix

$$L = \begin{pmatrix} \sum_{j=2}^{N} a_{1j} & -a_{12} & \cdots & -a_{1N} \\ -a_{21} & \sum_{j=1, j\neq 2}^{N} a_{2j} & \ddots & \vdots \\ \vdots & \ddots & \ddots & -a_{(N-1)N} \\ -a_{N1} & \cdots & -a_{N(N-1)} & \sum_{j=1}^{N-1} a_{Nj} \end{pmatrix}$$

with $a_{ij} = 0$ if (and only if) $j \notin \mathcal{N}_i$

Eigenvalues of L:

$$0 = \lambda_1 < \lambda_2 \leq \ldots \leq \lambda_N$$

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Assumption: there exists a permutation matrix Π that commutes with L

$$\Pi L = L \Pi$$

Partial synchronization

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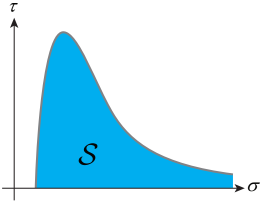
$$\Pi L = L \Pi$$

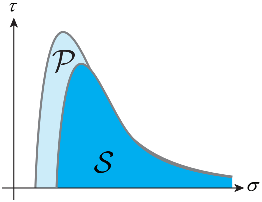
Denote

- λ' the smallest eigenvalue of L with eigenvector in $\text{range}(I_N - \Pi)$
- λ^* the largest eigenvalue of L with eigenvector in $\text{range}(I_N - \Pi)$

Partial synchronization



$\lambda' = \lambda_2$ and $\lambda^* = \lambda_N$



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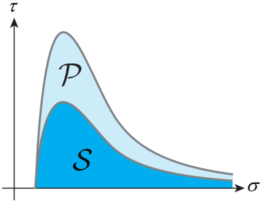

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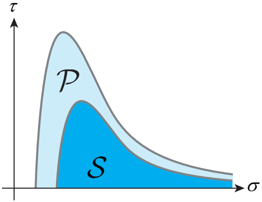

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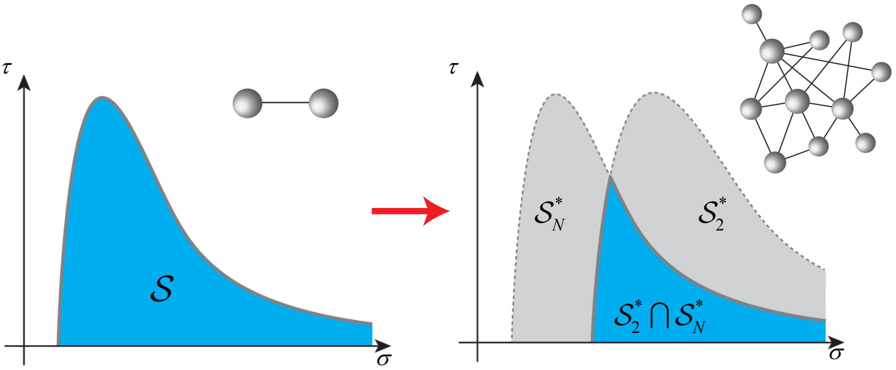
Scaling with the non-zero eigenvalues of L



$$\mathcal{S}_j^* := \left\{ (\sigma, \tau) \in \mathbb{R}_+ \times \overline{\mathbb{R}}_+ \,\middle|\, \left(\frac{\lambda_j}{2}\sigma, \tau \right) \in \mathcal{S} \right\}$$

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Recap

Experimental setup

Performing experiments

Networks of Hindmarsh-Rose neurons

The Hindmarsh-Rose model neuron:

$$\begin{aligned}
\dot{z}_{i,1} &= 100(-y_i^2 - 2y_i - z_{i,1}) \\
\dot{z}_{i,2} &= 0.5(4y_i + 4.472 - z_{i,2}) \\
\dot{y}_i &= 100\big(-y_i^3 + 3y_i - 8 + 5z_{i,1} - z_{i,2} + 3.3 + u_i\big)
\end{aligned}$$

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Properties:

- strictly semi-passive with a quadratic storage function of the form

$$S = \frac{1}{200} y_i^2 + c_1 z_{i,1}^2 + c_2 z_{i,2}^2$$

for some $c_1, c_2 > 0$

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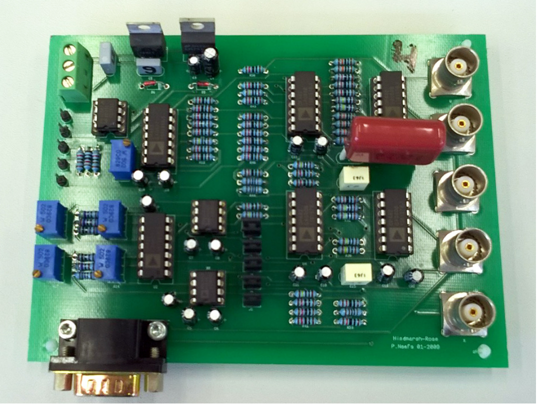
  for some $c_1, c_2 > 0$
- z_i-dynamics satisfy the test for exponential convergence with $P = I$

Hindmarsh-Rose electronic neuron



Networks of Hindmarsh-Rose neurons

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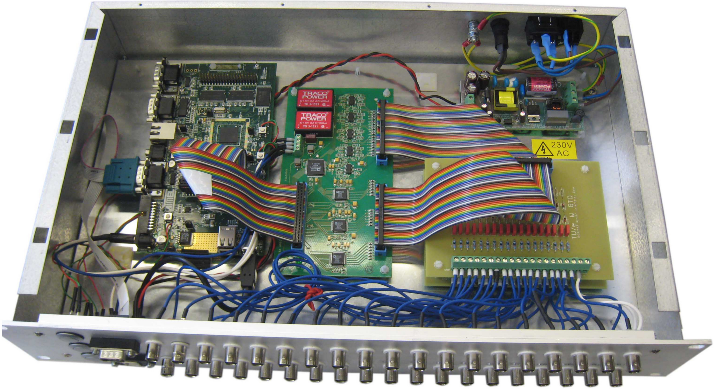
with time-delay coupling functions

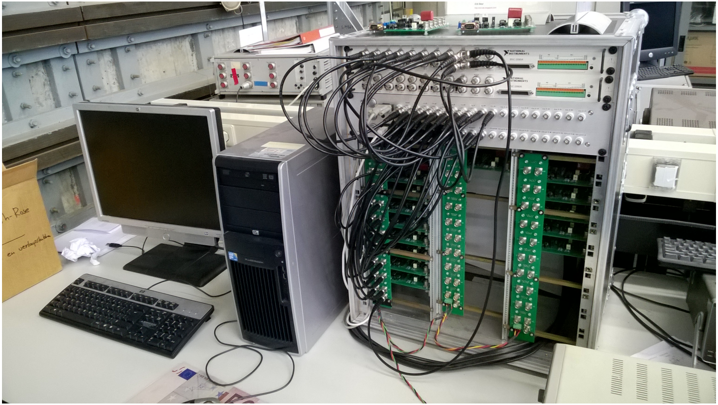
$$u_i(t) = \sigma \sum\nolimits_{j \in \mathcal{N}_i} a_{ij}(y_j(t - \tau) - y_i(t - \tau))$$

where $a_{ij} = a_{ji} > 0$ and $j \in \mathcal{N}_i \Leftrightarrow i \in \mathcal{N}_j$

Coupled Hindmarsh-Rose electronic neurons



Coupled Hindmarsh-Rose electronic neurons



Synchronization experiments

Due to

- imperfections in the hardware realizations
- un-modeled dynamics, e.g. noise

synchronization (or partial synchronization) in the sense that

$$x_i(t) = x_j(t)$$

is not possible

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Practical (partial) synchronization: outputs $y_i(t)$ and $y_j(t)$, defined o a finite interval $t \in [t_0,\ t_2]$, converge towards each other within a "sufficiently small" bound ε:

$$\exists t_1 \in [t_0,\ t_2) \text{ such that } \|y_i(t) - y_j(t)\| \leq \varepsilon \text{ for all } t \in [t_1, t_2]$$

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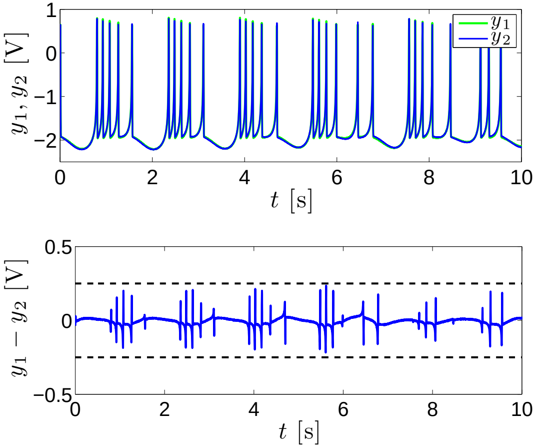
Practical synchronization with bound $\varepsilon = 0.25$

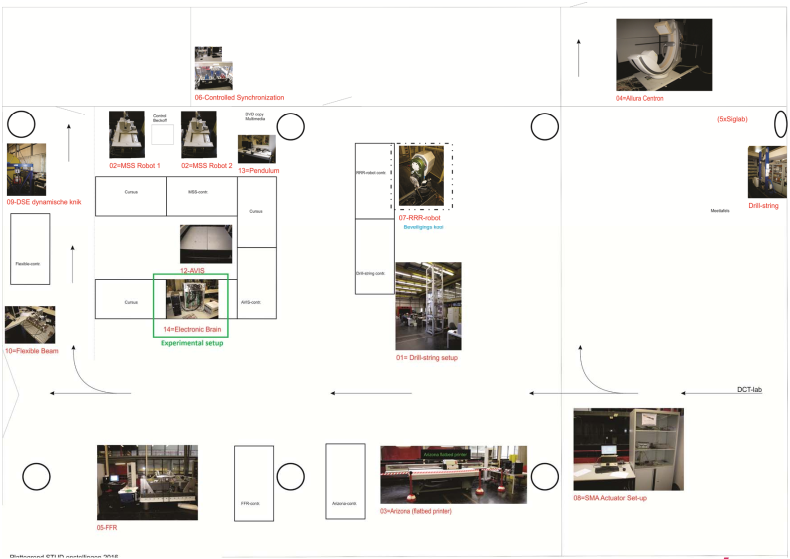


Recap

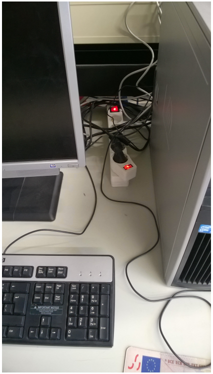
Experimental setup

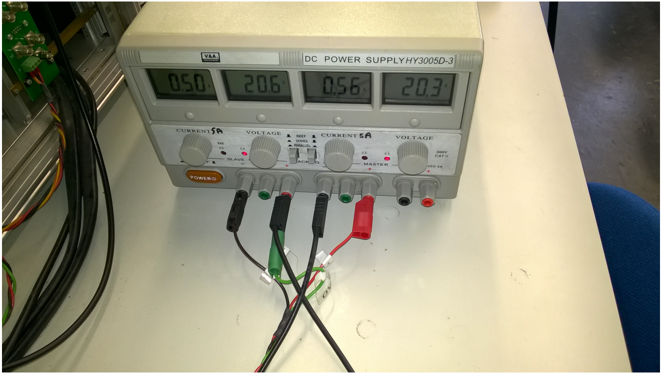
Performing experiments

Location setup: DCT lab (Gem-Z -1.13)



Powering the setup





Software

- Login PC
  - User: `HRsync`
  - Password: `NI6363sync`

Software

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- Open folder: `4dm50_experiments`

Software

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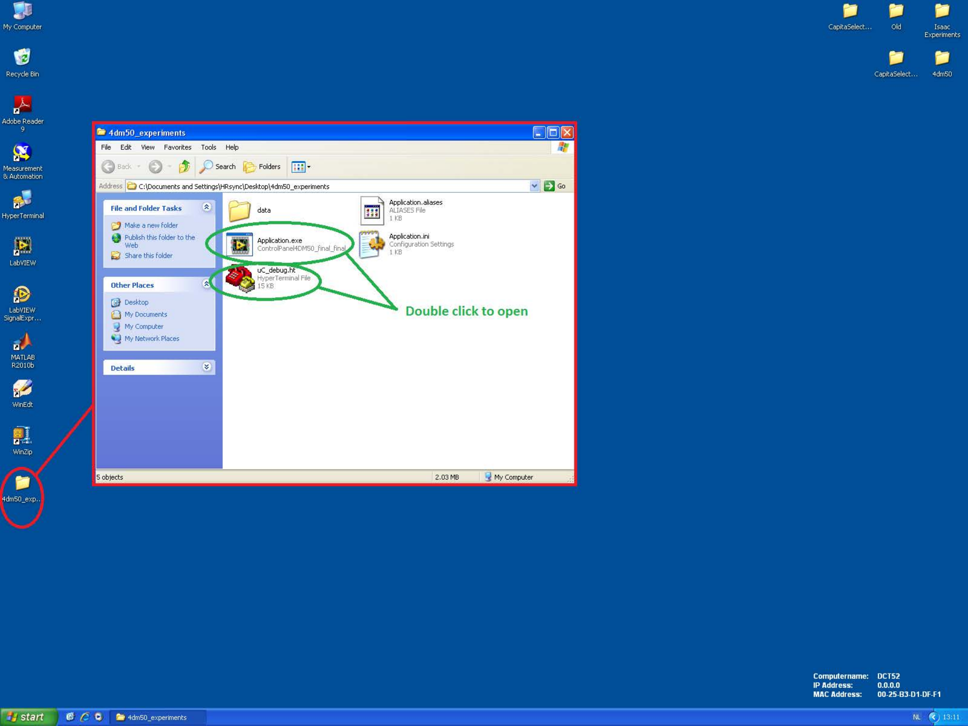
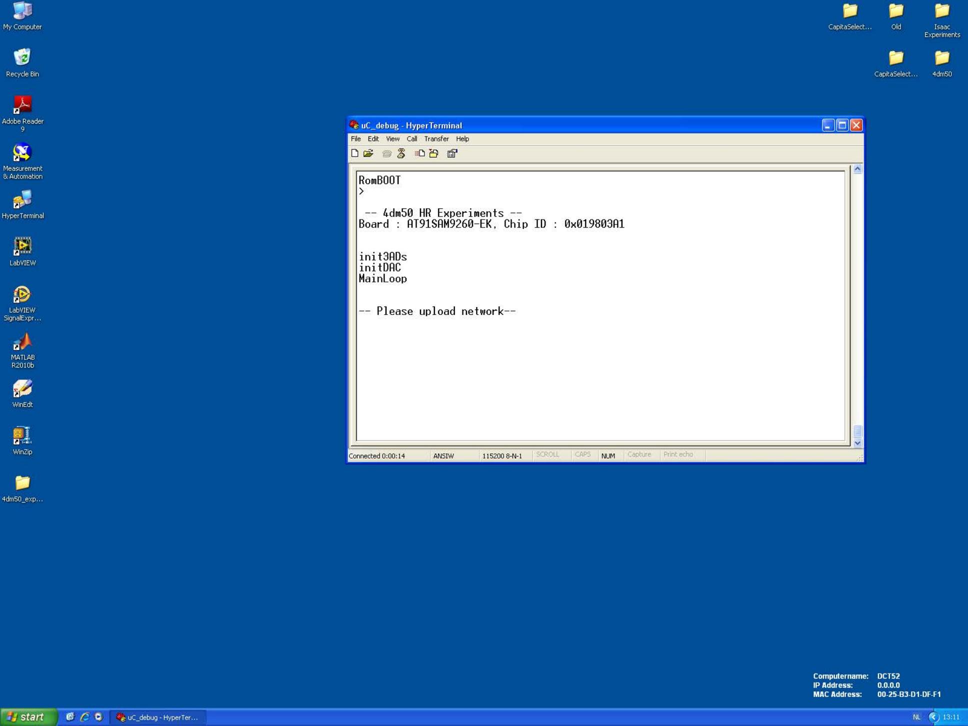
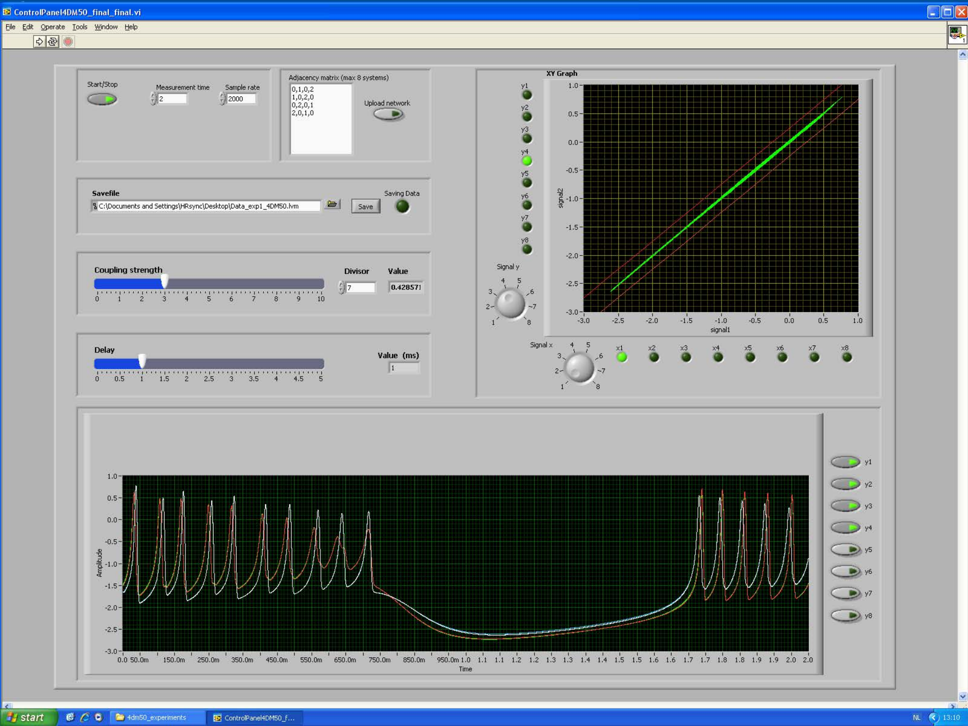
- Open: `uC_debug.ht` and `Application.exe`


My Computer
Recycle Bin
Adobe Reader 9
Measurement & Automation
HyperTerminal
LabVIEW
LabVIEW SignalExpr...
MATLAB R2010b
WinEdt
WinZip
4dm50_exp...
CapitaSelect...
Old
Isaac Experiments
CapitaSelect...
4dm50
4dm50_experiments
File Edit View Favorites Tools Help
Back Search Folders
Address C:\Documents and Settings\HRsync\Desktop\4dm50_experiments Go
File and Folder Tasks
Make a new folder
Publish this folder to the Web
Share this folder
Other Places
Desktop
My Documents
My Computer
My Network Places
Details
data
Application.aliases
ALIASES File
1 KB
Application.exe
ControlPanel4DM50_final_final
Application.ini
Configuration Settings
1 KB
uC_debug.ht
HyperTerminal File
15 KB
Double click to open
5 objects
2.03 MB
My Computer
Computername: DCT52
IP Address: 0.0.0.0
MAC Address: 00-25-B3-D1-DF-F1
start
4dm50_experiments
NL
13:11



uC_debug - HyperTerminal
File Edit View Call Transfer Help
RomBOOT
>
-- 4dm50 HR Experiments --
Board : AT91SAM9260-EK, Chip ID : 0x019803A1
init3ADs
initDAC
MainLoop
-- Please upload network--
Connected 0:00:14 ANSIW 115200 8-N-1 SCROLL CAPS NUM Capture Print echo
My Computer
Recycle Bin
Adobe Reader 9
Measurement & Automation
HyperTerminal
LabVIEW
LabVIEW SignalExpr...
MATLAB R2010b
WinEdt
WinZip
4dm50_exp...
CapitaSelect...
Old
Isaac Experiments
CapitaSelect...
4dm50
Computername: DCT52
IP Address: 0.0.0.0
MAC Address: 00-25-B3-D1-DF-F1
start
uC_debug - HyperTer...
NL 13:11


ControlPanel4DM50_final_final.vi
File Edit Operate Tools Window Help
Start/Stop
Measurement time
2
Sample rate
2000
Adjacency matrix (max 8 systems)
0,1,0,2
1,0,2,0
0,2,0,1
2,0,1,0
Upload network
Savefile
C:\Documents and Settings\HRsync\Desktop\Data_exp1_4DM50.lvm
Save
Saving Data
Coupling strength
Divisor
7
Value
0.428571
Delay
Value (ms)
1
XY Graph
y1
y2
y3
y4
y5
y6
y7
y8
Signal y
signal2
signal1
Signal x
x1
x2
x3
x4
x5
x6
x7
x8
Amplitude
Time
start
4dm50_experiments
ControlPanel4DM50_f...
NL
13:10

Starting the experiments

1. Press `Run Continuously` button

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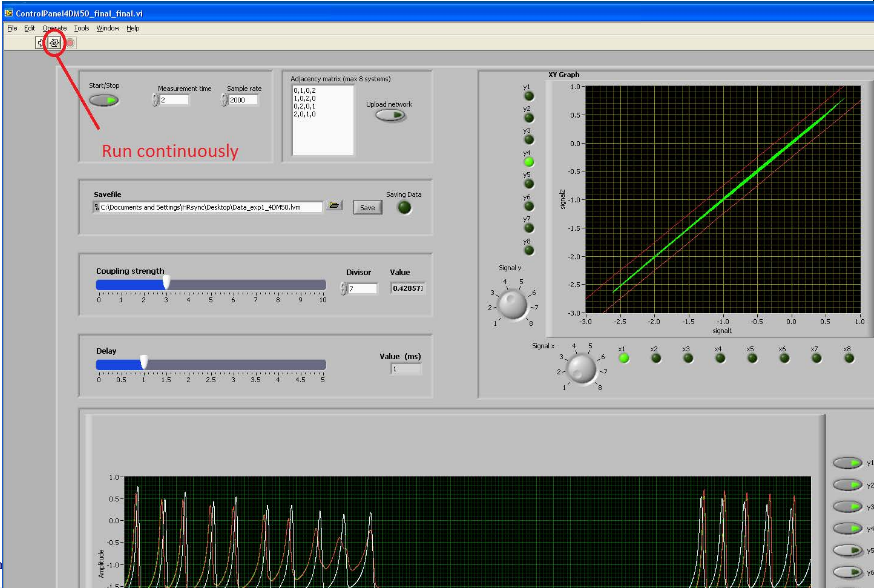

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Uploading the network

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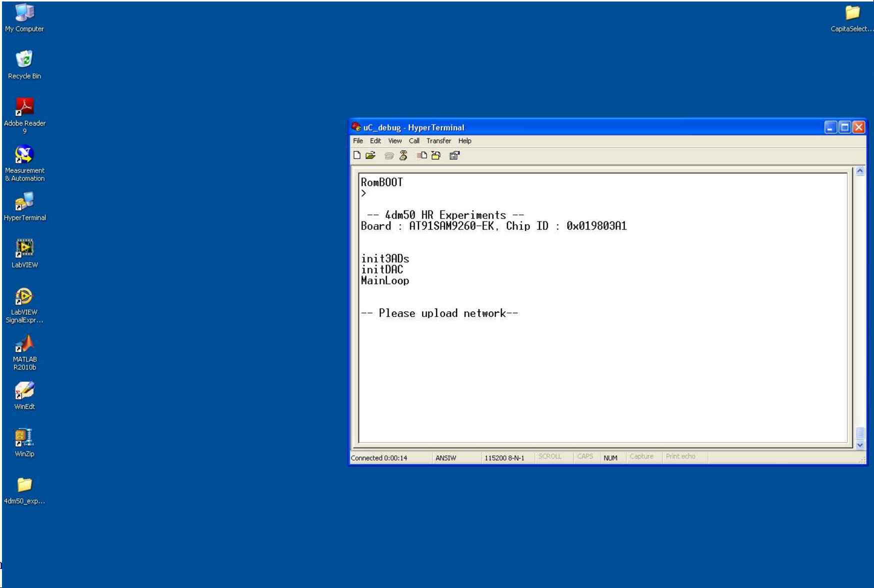

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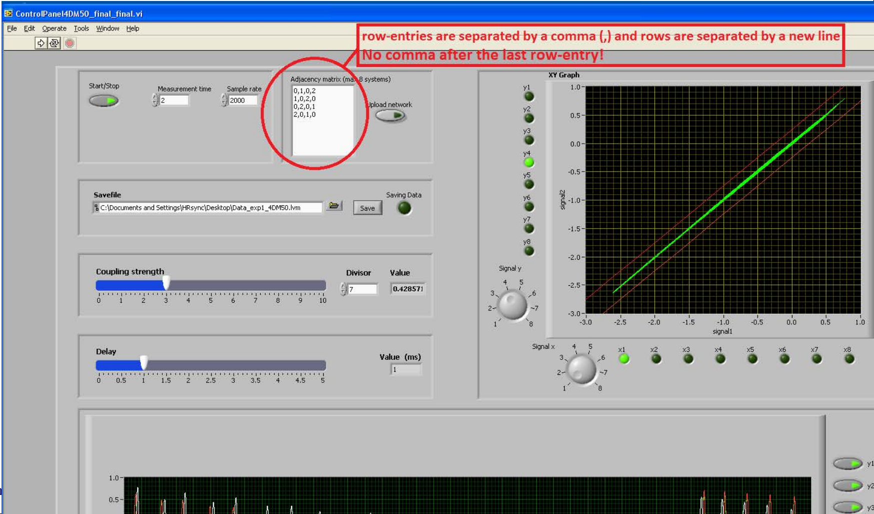

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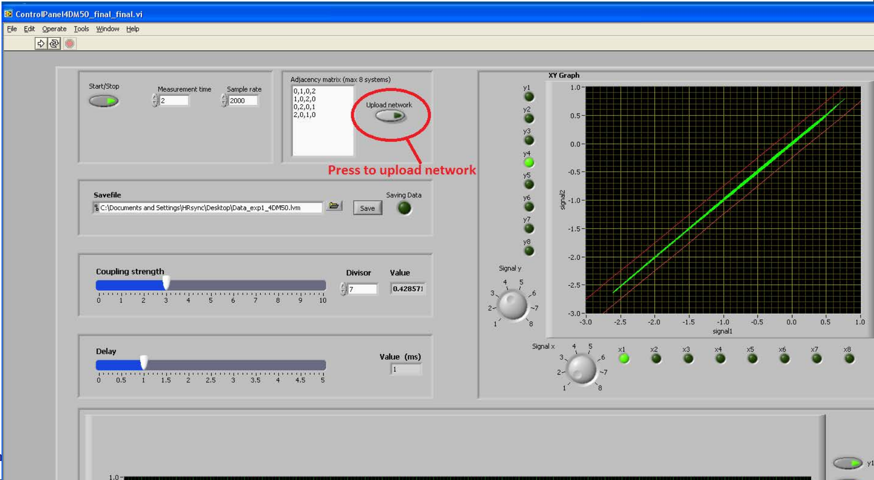

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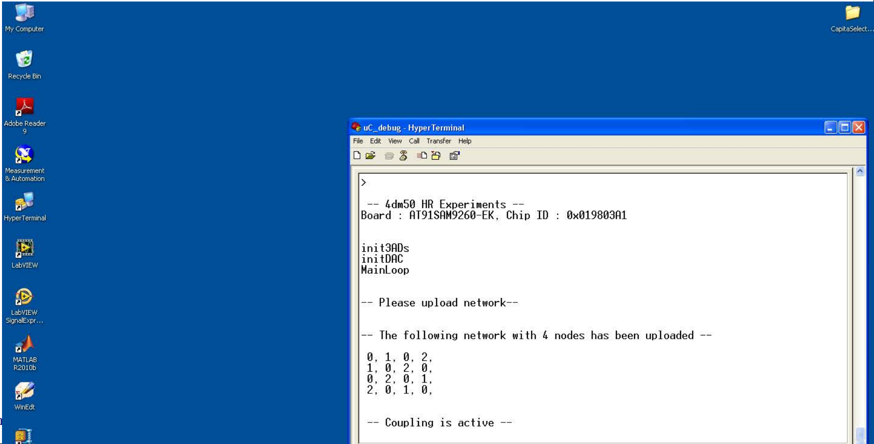
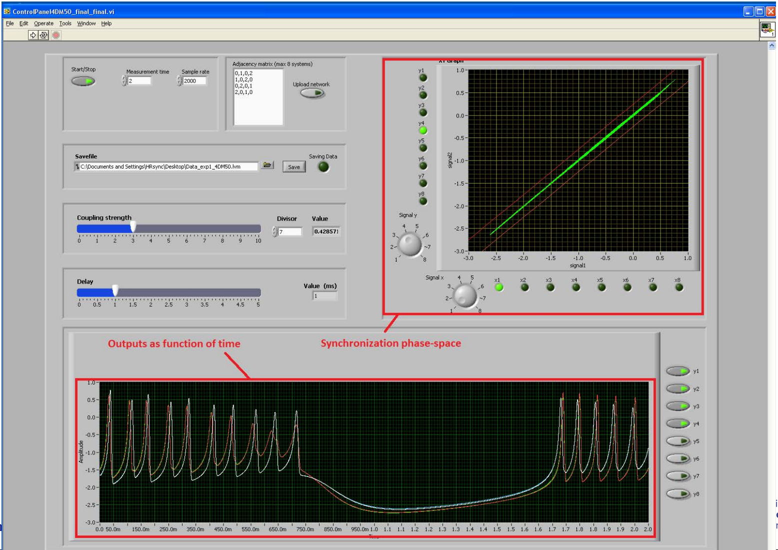


Synchronization experiments

1. Select the outputs you want to visualize
   (Visualized output(s) are indicated by the bright green “led(s)”)



Synchronization experiments

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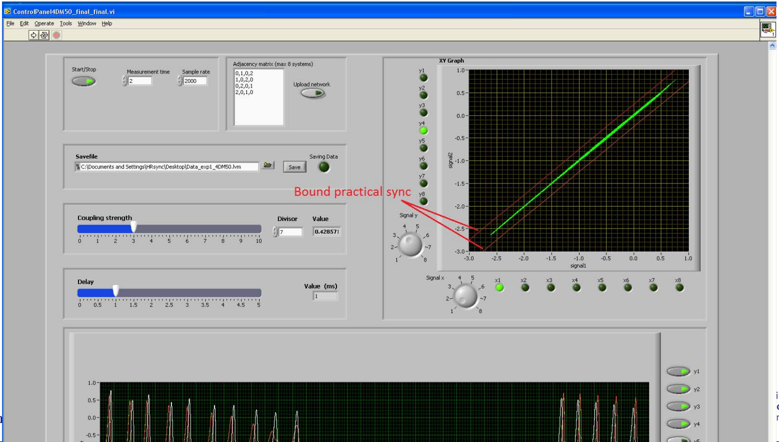
3. Identity practical (partial) synchronization



Saving data

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3. Press `Save` to start saving data
   - Saving data starts when the saving data indicator turns green
   - Saving data is completed when the saving data indicator turns off

Data file

The data files (.lvm) can be opened with a text editor or may be imported in Matlab

Time Neuron1 Neuron2 ... Neuron8

CapitaSelectaDataTau1a - Notepad

File Edit Format View Help

0.000000	-2.182114	-2.188239	-2.176311	-2.186950	-2.171798	-2.209194	-2.175344	-2.177923
0.000100	-2.183081	-2.188562	-2.177278	-2.188239	-2.170831	-2.207904	-2.175666	-2.177923
0.000200	-2.183081	-2.186950	-2.175666	-2.186627	-2.171153	-2.208227	-2.174699	-2.178568
0.000300	-2.181469	-2.188239	-2.176311	-2.186950	-2.172443	-2.208872	-2.175022	-2.177601
0.000400	-2.182114	-2.191141	-2.176634	-2.187917	-2.172120	-2.207582	-2.175022	-2.177923
0.000500	-2.181792	-2.188884	-2.175989	-2.187594	-2.170831	-2.208227	-2.175022	-2.178245
0.000600	-2.182114	-2.189206	-2.176311	-2.187917	-2.171798	-2.207260	-2.175022	-2.178245
0.000700	-2.183081	-2.189851	-2.177601	-2.186950	-2.171153	-2.208872	-2.175344	-2.178568
0.000800	-2.182436	-2.188884	-2.175666	-2.187594	-2.171475	-2.209839	-2.173732	-2.178245
0.000900	-2.182436	-2.188562	-2.177923	-2.187917	-2.169541	-2.208549	-2.175022	-2.177601
0.001000	-2.184371	-2.188884	-2.175989	-2.186627	-2.171798	-2.208549	-2.175666	-2.178890
0.001100	-2.183081	-2.188562	-2.177278	-2.187272	-2.172765	-2.208227	-2.175666	-2.177278
0.001200	-2.182436	-2.191141	-2.178245	-2.187594	-2.171153	-2.209194	-2.174699	-2.177923
0.001300	-2.182759	-2.188239	-2.176311	-2.187917	-2.171798	-2.209516	-2.175989	-2.180502
0.001400	-2.182759	-2.189529	-2.176311	-2.188239	-2.171153	-2.210483	-2.175989	-2.178890
0.001500	-2.183404	-2.190818	-2.176956	-2.188239	-2.171153	-2.209194	-2.175666	-2.178890
0.001600	-2.183404	-2.188239	-2.176311	-2.187272	-2.171475	-2.209194	-2.176311	-2.178568
0.001700	-2.182759	-2.189529	-2.177601	-2.188562	-2.172443	-2.208549	-2.175344	-2.179535
0.001800	-2.185338	-2.192108	-2.177278	-2.188239	-2.171153	-2.208549	-2.175989	-2.179857
0.001900	-2.183726	-2.188884	-2.177601	-2.188884	-2.172120	-2.210483	-2.175022	-2.178568
0.002000	-2.183081	-2.189529	-2.178568	-2.186627	-2.172120	-2.207904	-2.174699	-2.178890
0.002100	-2.184693	-2.188562	-2.176311	-2.187594	-2.172443	-2.209194	-2.176956	-2.178890
0.002200	-2.183404	-2.189206	-2.177601	-2.188884	-2.173732	-2.209839	-2.175666	-2.179535
0.002300	-2.183726	-2.191141	-2.175022	-2.188562	-2.172120	-2.208549	-2.176634	-2.179857
0.002400	-2.182759	-2.187917	-2.176634	-2.187917	-2.171798	-2.210161	-2.176311	-2.178890
0.002500	-2.183404	-2.189206	-2.177923	-2.189206	-2.175344	-2.208549	-2.175666	-2.179213
0.002600	-2.185660	-2.189529	-2.177278	-2.188562	-2.172120	-2.209516	-2.176311	-2.178890
0.002700	-2.183081	-2.188884	-2.177278	-2.188239	-2.171798	-2.209839	-2.175022	-2.179213
0.002800	-2.184048	-2.190818	-2.178568	-2.189851	-2.172765	-2.209516	-2.175989	-2.180180
0.002900	-2.184371	-2.189206	-2.177923	-2.188884	-2.173087	-2.209516	-2.176956	-2.180180
0.003000	-2.184048	-2.189529	-2.177923	-2.188884	-2.173410	-2.208872	-2.175666	-2.179213
0.003100	-2.183726	-2.190174	-2.178568	-2.189529	-2.171798	-2.209516	-2.176311	-2.180180
0.003200	-2.182759	-2.189851	-2.176956	-2.188562	-2.172443	-2.209194	-2.176956	-2.179857
0.003300	-2.183404	-2.191141	-2.177601	-2.190174	-2.172443	-2.208872	-2.176634	-2.180180
0.003400	-2.184048	-2.191785	-2.177278	-2.187594	-2.172443	-2.209839	-2.176311	-2.179213
0.003500	-2.183726	-2.190174	-2.177601	-2.188562	-2.172443	-2.210806	-2.175989	-2.180502
0.003600	-2.184371	-2.190818	-2.179213	-2.189529	-2.172120	-2.209194	-2.176634	-2.179857
0.003700	-2.185983	-2.189529	-2.177278	-2.187917	-2.172443	-2.209516	-2.176311	-2.180180
0.003800	-2.184048	-2.189851	-2.178245	-2.189529	-2.173732	-2.210483	-2.177278	-2.179535
0.003900	-2.184693	-2.191141	-2.178568	-2.188239	-2.173087	-2.209194	-2.176956	-2.180180
0.004000	-2.184371	-2.190496	-2.178568	-2.189206	-2.173087	-2.210161	-2.177601	-2.181147
0.004100	-2.183404	-2.190174	-2.177601	-2.189529	-2.173410	-2.209516	-2.176311	-2.179857
0.004200	-2.184693	-2.192108	-2.179213	-2.188884	-2.173410	-2.210483	-2.175989	-2.180825
0.004300	-2.185983	-2.191141	-2.177278	-2.189529	-2.172443	-2.210161	-2.177923	-2.180180
0.004400	-2.184048	-2.191785	-2.178568	-2.190496	-2.171475	-2.210483	-2.176311	-2.180180
0.004500	-2.185983	-2.192108	-2.176956	-2.188884	-2.173410	-2.210161	-2.176634	-2.180825
0.004600	-2.185015	-2.190174	-2.177923	-2.189206	-2.173087	-2.210806	-2.178245	-2.178890
0.004700	-2.185338	-2.190818	-2.179213	-2.187272	-2.173087	-2.210161	-2.176634	-2.180180
0.004800	-2.186627	-2.189851	-2.177278	-2.188884	-2.173087	-2.210161	-2.177601	-2.181147
0.004900	-2.184048	-2.189851	-2.178568	-2.190174	-2.175022	-2.212740	-2.177601	-2.180502
0.005000	-2.184371	-2.192753	-2.177923	-2.189206	-2.173732	-2.210161	-2.176956	-2.180180
0.005100	-2.185015	-2.189529	-2.178245	-2.188884	-2.173410	-2.211128	-2.177923	-2.180180
0.005200	-2.184371	-2.190496	-2.177923	-2.190496	-2.175022	-2.210806	-2.177278	-2.180180
0.005300	-2.185983	-2.191463	-2.178245	-2.190174	-2.174377	-2.210483	-2.177601	-2.181147
0.005400	-2.185015	-2.190818	-2.177601	-2.189851	-2.173087	-2.211128	-2.176634	-2.179535

After your experiments: Power off!