TerraSwarm

A Data-driven Synchronization Technique for Cyber-Physical Systems

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Introduction

- The number of environmental sensors is rapidly growing
- Synchronization between the sensors in the system is critical for data fusion, estimation, and other signal processing
- Data between sensors may be unsynchronized due to
  - Inaccurate clock sources
  - Delays in time stamping
  - Wireless transmission delays

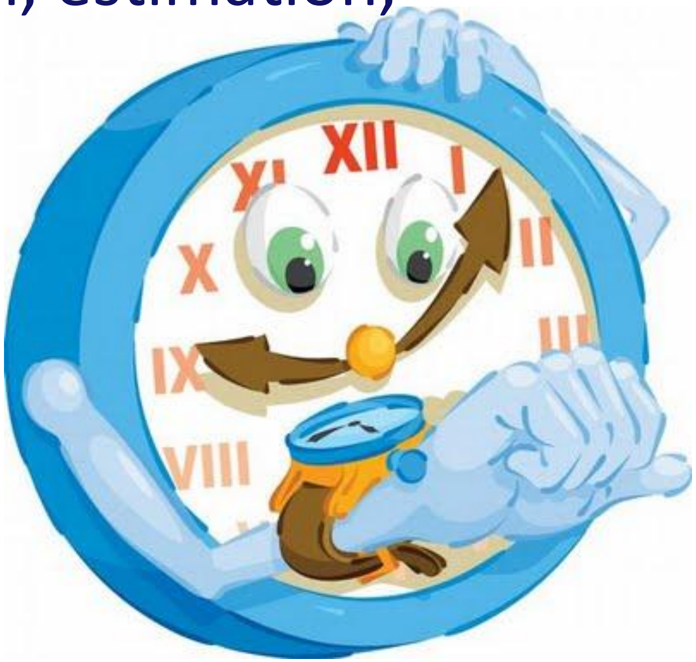


Image from http://blog.onlineclock.net/

Motivation

- Homogeneity cannot be guaranteed in a Swarm of sensors
  - Wireless Data Transmission
  - Grid based power supply
  - Infrastructure/Environmental
  - Locally Stored Data
  - Battery Powered
  - Mobile/Wearable
- All sensors provide a data stream and related timestamps
- How can we use the events measured by the sensors to synchronize the sensor data

Image from www.ti.com

Contributions

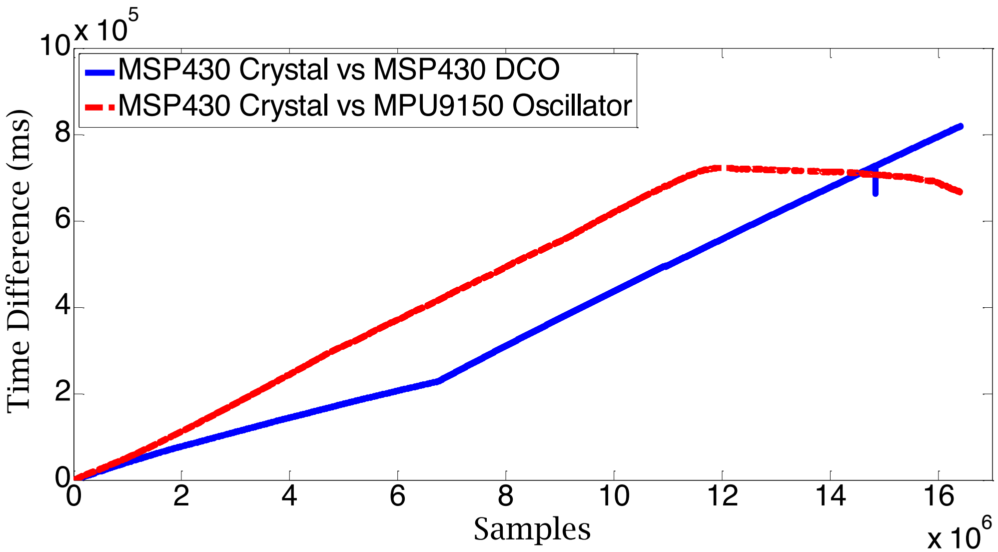
- Offline technique for synchronizing sensor timing based on the sensor data
  - Use the physical world to synchronize data in the cyber world
  - Works with heterogeneous sensor data
- Methods to determine the physical or cyber events (i.e. couplings) in the sensor data streams that can be used for synchronization
- Methods to select a subset of the couplings to best improve the system synchronization

Background

- Variety of clock generation circuits
- Typically trade off power for accuracy
  - Crystal Oscillators: $\pm 20ppm$
  - Digitally Controlled Oscillators: $\pm 5000ppm$
  - Voltage Controlled/Relaxation Oscillators: $\pm 10000ppm$
- Oscillator inaccuracy and drift lead to clock errors and require synchronization

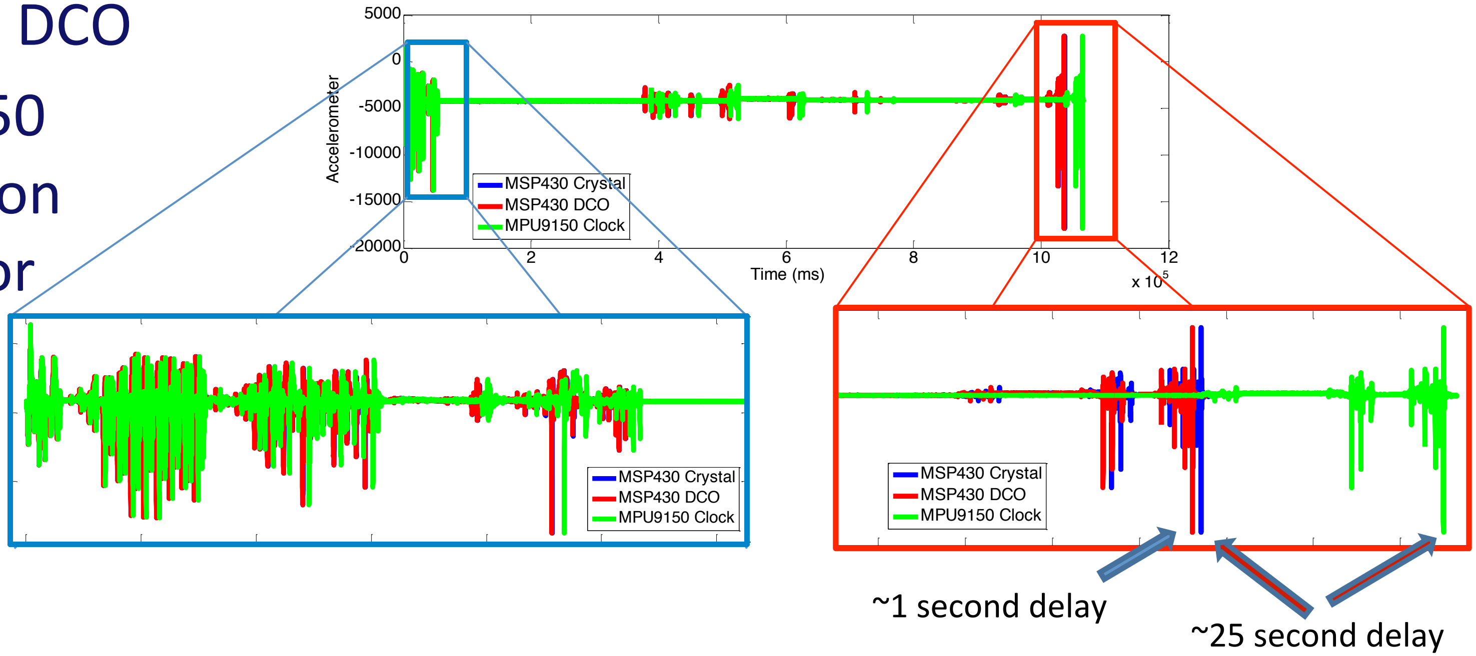
Sensor Clocking Test 1

- Single sensor with local storage
- ~22.5 hour run time
- Greater than 10 minutes of error over the collection
- Inconsistent clock due to battery



Sensor Clocking Test 2

- Sensor Test
  - 17 minutes of data
    - MSP430 Crystal
    - MSP430 DCO
    - MPU9150 Relaxation Oscillator



Assumptions

- Difficult to control the quality of the clocks/time synchronization schemes in the presence several billions of sensors:
  - Some sensors may not have accurate clocks (due to power or cost constraints)
  - Some sensors may not be capable of supporting communication to enable time synchronization
  - Data from sensors cannot be effectively used if an acceptable level of time synchronization is not present
  - Data fusion from various sensors presents significant value that cannot be discarded

Two Sensor Alignment Formulation

- Sensors S_1 and S_2 are making measurements of a physical phenomenon
- *Each sensor makes observations*: $o_i^n = \{x_i^n, t_i^n\}$
  - $n \in \{1,2\}$ is the sensor number
  - $i \in \mathbb{N}$ is the observation number
  - x_i^n and t_i^n are the data and timestamp for the observation respectively

Alignment Points

- **Definition:** An alignment point (AP) is a representation of a physical or cyber event in a sensor data stream that can be accurately distinguished and directly related to the same event in the data stream of another sensor (*i.e.* physical or cyber coupling)

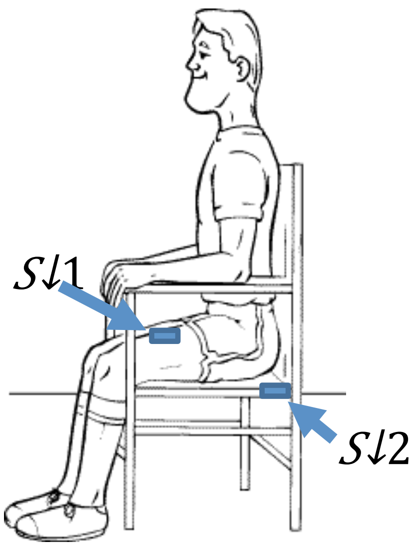
$$o_i^k \equiv o_j^l \text{ where } k \neq l$$

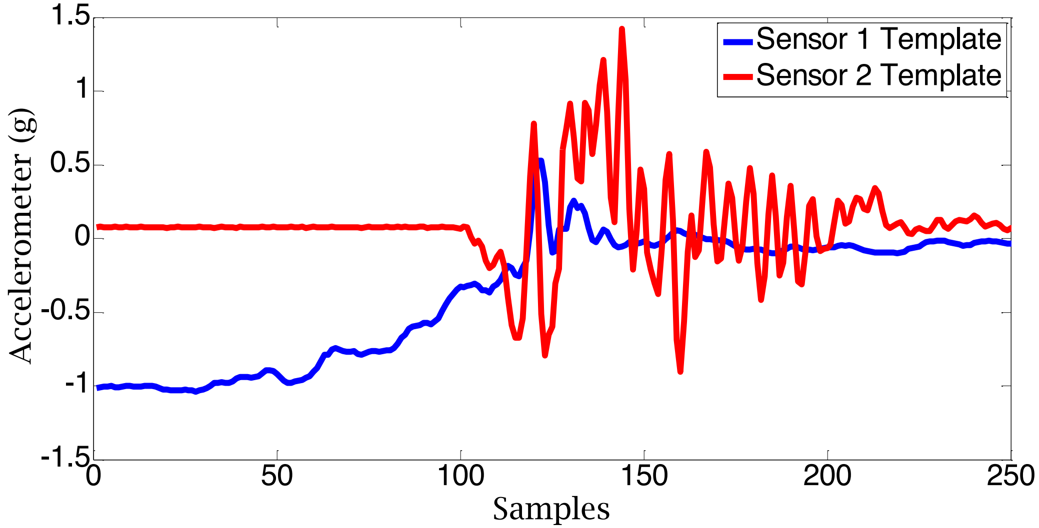
$$\boldsymbol{A} = \{(o_i^k, o_j^l) \mid \exists\, i,k,j,l \text{ such that } o_i^k \equiv o_j^l\}$$

- We use the alignment points to correct the less accurate clock

Template Based AP Selection

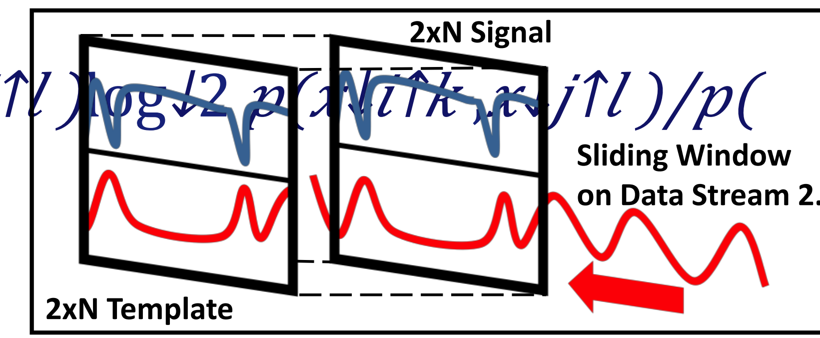
- Synchronized templates of sensor interactions
  - Example:





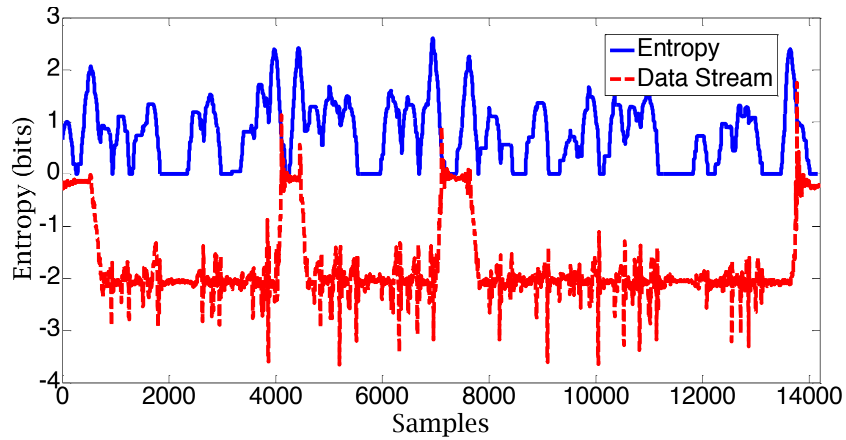
Template Based AP Selection 2

- Use Dynamic Time Warping (DTW) to match the S_1 data stream
  - Matching not sensitive to speed variation
- Use Mutual Information to match the S_2 data stream to the S_1 data stream and the template
- $I(X^k;X^l)=\sum p(x_i^k,x_j^l)\log_2 p(x_i^k,x_j^l)/p(x_i^k)p(x_j^l)$



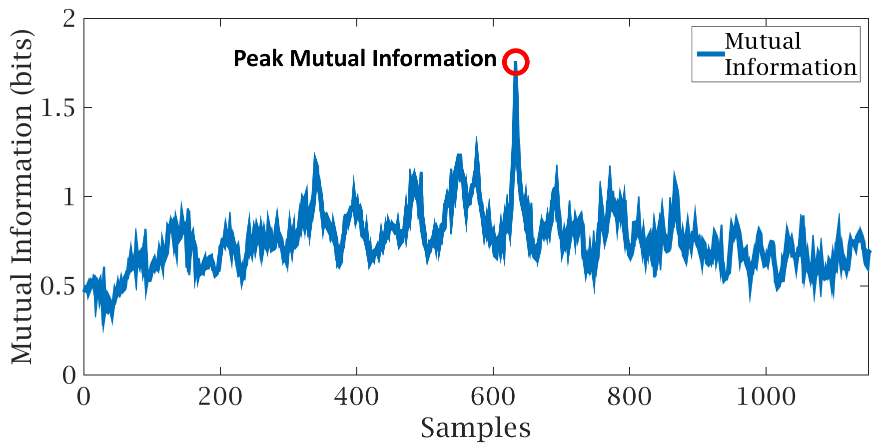
Entropy Based AP Selection

- The two sensors are measuring the same physical phenomena, but there is limited knowledge of the sensor data streams
- Entropy is a measure of information content
  - $H(X^n) = -\sum p(x_i^n) \log_2 p(x_i^n)$
  - The parts of the data with the highest entropy are considered useful for matching



Entropy Based AP Selection 2

- Use peaks of the entropy calculation to determine segments of the S_1 data to match against S_2 data
- Use mutual information to match the data streams
- The peak of the mutual information calculations is the matching segment from S_2



AP Subset Selection

- Entropy based AP selection can generate many possible segments for matching
- Select a subset of the APs $\boldsymbol{S} \subseteq \boldsymbol{A}$ for synchronization
- Two methods to select a subset of APs
  - Regional Peak Selection
  - Binary Search Selection

Regional Peak Selection

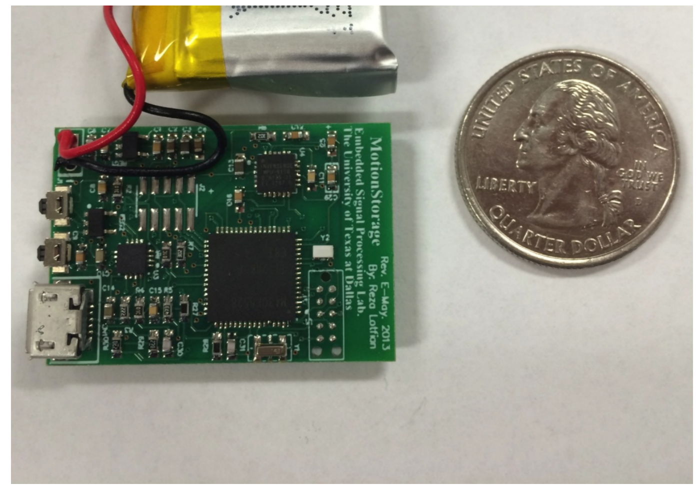
- Based on a quality score, q_i, position, p_i, and a region, R, select $\boldsymbol{S}$
- Use the entropy value as the quality score, sort all alignment points, $a_i \in \boldsymbol{A}$
  - $a_i \in \mathbf{S}$ iff $\max(q_i)$, $|p_i - p_j| > R$ and $i > j$
- Prioritizes quality while spreading alignments across the signal

Binary Search Selection

- Based on bisections of the data stream, find the entropy peak closest to the binary positions
- Select a level, L, to generate up to $2^{L}-1$ points at positions, l_k
  - $a_i \in \mathbf{S}$ iff $|p_i - l_k| < |p_j - l_k|, \forall\ l_k$
- Prioritizes equal spacing of alignment points across the data stream

Experiments

- Sensor
  - TI MSP430
  - Invensense MPU9150
  - Bluetooth data transmission

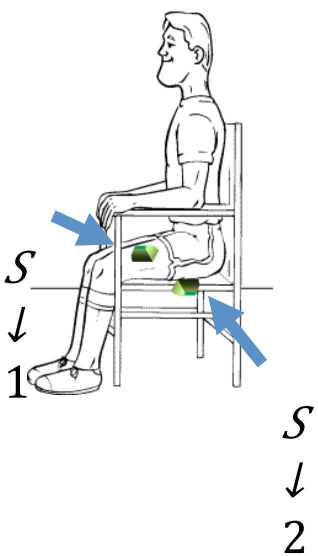


- Experiments
  - Template Based
  - Entropy Based

Template Based Experiments for two Sensor Synchronization

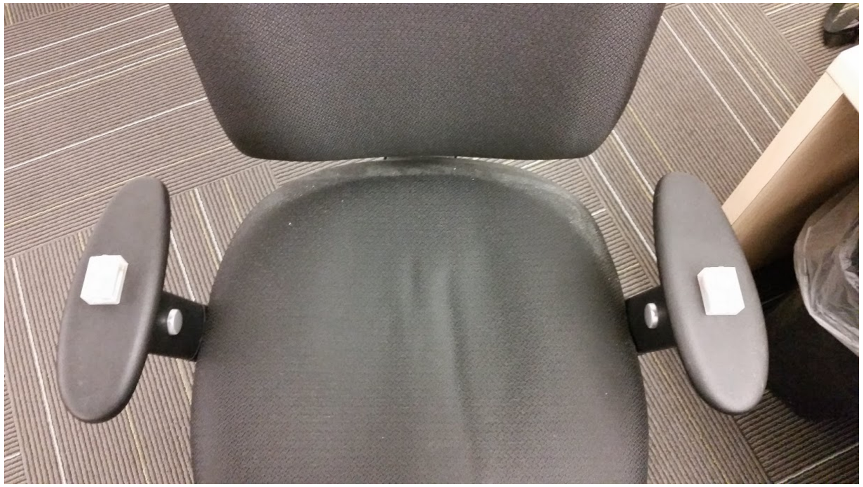
- Three experiments using templates

Experiment Number	S_1 location	S_2 location
1	Subject’s Right Thigh	Office Chair Arm
2	Subject’s Right Wrist	Office Door
3	Turntable Arm	Turntable Platter



Entropy Based Experiments

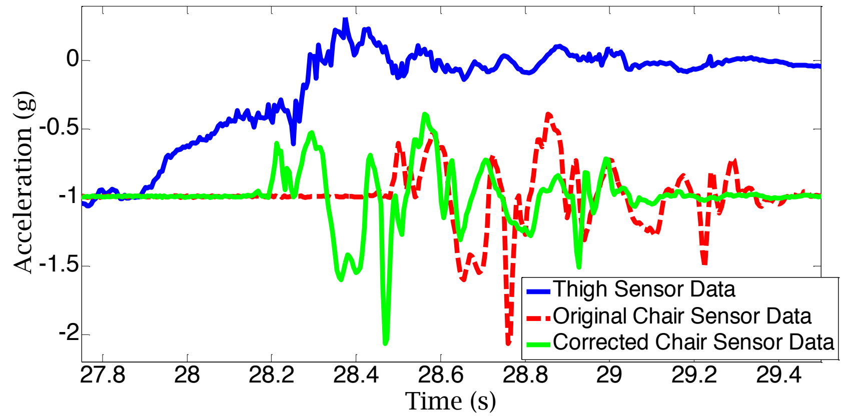
- Sensors measuring the same phenomenon
  - Stacked Sensors
  - Two Sensors on opposite arms of a chair



Metrics & Template Experiment Results

- Metrics
  - $ppm = \Delta t / T \times 1{,}000{,}000$
  - $E_{nTot} = \sum_{i}^{n} |t_i - t_i| / n$

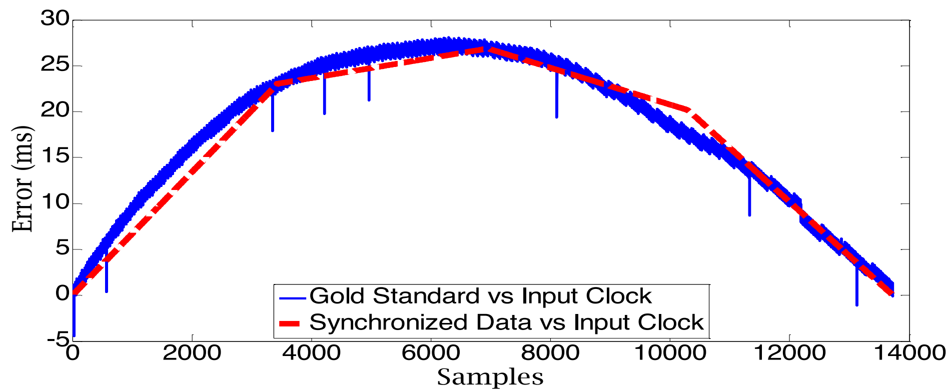
Template Based Method				
Experiment	Thigh, Chair	Wrist, Door	Turn-table	Original
E_{nTot} (ms)	72.8	51.6	22.9	13.3
ppm	5,131.1	1,862.2	199.9	11,907



Entropy Experiment Results

Non-Template Binary Search Method				
Experiment		Stacked	Two on Chair	Original
***E_{nTot}* (ms)**	***min***	1.2	6.0	10.9
	max	16.4	24.9	216.1
	avg	5.9	11.4	70.2
ppm	***min***	35.3	291.8	11,443
	max	423.5	513.0	14,259
	avg	195.8	359.2	12,224

Non-Template Region Peak Method				
Experiment		Stacked	Two on Chair	Original
***E_{nTot}* (ms)**	***min***	2.9	10.4	10.9
	max	27.4	33.2	216.1
	avg	7.4	27.3	70.2
ppm	***min***	107	215.7	11,443
	max	529.1	838.9	14,259
	avg	208.5	680.7	12,224



Conclusions

- Sensor-rich environments are likely to have heterogeneous sensors
- Synchronization increases the value of data received from these systems
- An offline synchronization technique can be beneficial for synchronizing TerraSwarm data
- Cyber and physical couplings can be used to synchronize the data in an offline manner

Thanks & Questions