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Structural Health Monitoring For Bridge Infrastructure

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Los Alamos National Laboratory

Bridge-ing Big Data Workshop

Omaha, NE, October 8-9, 2015

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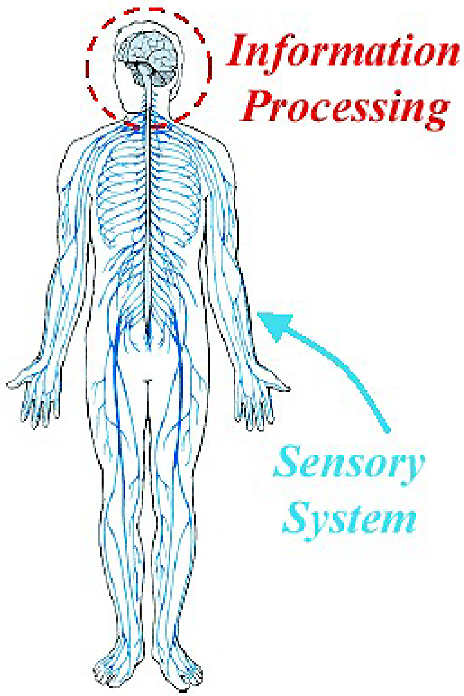
Structural Health Monitoring

Structural Health Monitoring (SHM) is the process of developing an ***online*** damage assessment capability for aerospace, civil, and mechanical infrastructure.



Prevent
This

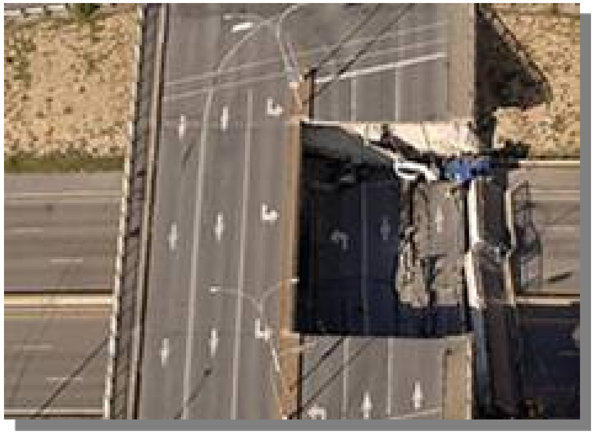
Motivation for SHM

Silver Bridge,
Pt Pleasant, WV
(1967, 46 dead)
US congress enacts mandatory bridge inspection

Song Su Bridge,
Seoul, South Korea (1994, 31 Dead)

Mianus Bridge, Greenwich, CT.
(June, 1983, 3 dead)

I-35 Bridge Collapse in MN
(2007, 13 dead)



Hwy 19 Overpass Collapse Quebec
(2006, 5 dead)

From: http://www.time.com/time/photogallery/0,29307,1649646_1421688,00.html
http://en.wikipedia.org/wiki/Bridge_collapse

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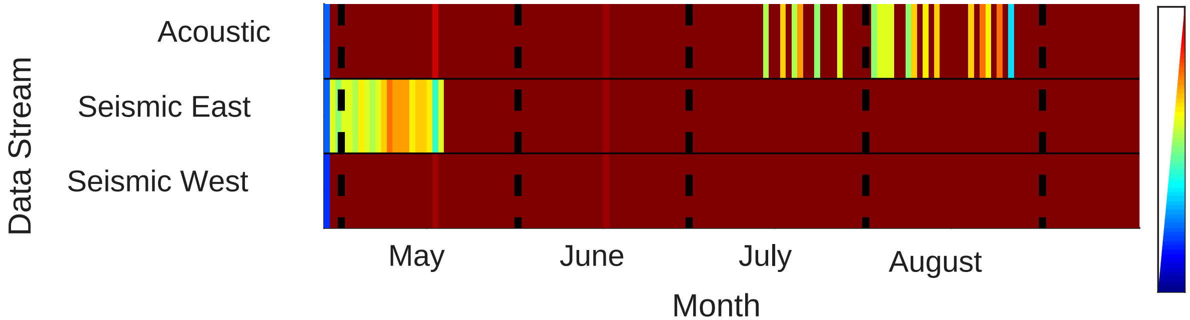
Recent Infrastructure Monitoring Project at LANL (Why "Big Data" is an issue)

- Nine sensors (3 acoustic, 6 accelerometers)
- Monitoring for 20 weeks, sampling at 250 Hz = 108 Gigabytes of data.
- **Very sparse instrumentation, very slow sampling for SHM**
- Not all the sensors worked 100% of the time



Percent of day operational

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Are These Systems Damaged?

Did you use pattern recognition?

The Structural Health Monitoring Process

- The Structural Health Monitoring process includes:

1. Operational evaluation

   Defines the damage to be detected , provides economic or life-safety justification for the monitoring system, and begins to answer questions regarding implementation issues for a structural health monitoring system.

2. Data acquisition & networking

   Defines the sensing hardware and the data to be used in the feature extraction process.

3. Feature selection & extraction

   The process of identifying damage-related information from measured data.

4. Probabilistic decision making

   Using statistical models to transform features into actual performance-level decisions

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State-of-the-Art Damage Detection Primarily Remains Visual Inspection (with local NDE)

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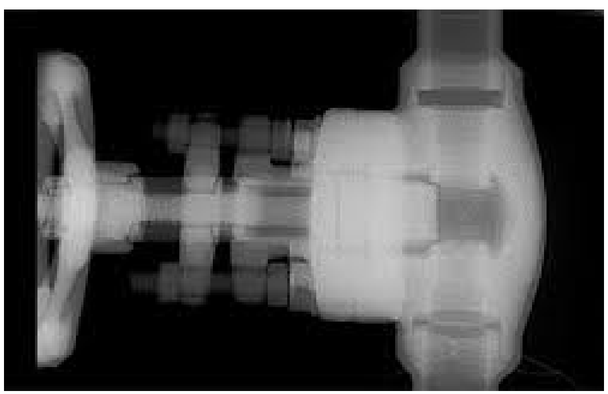
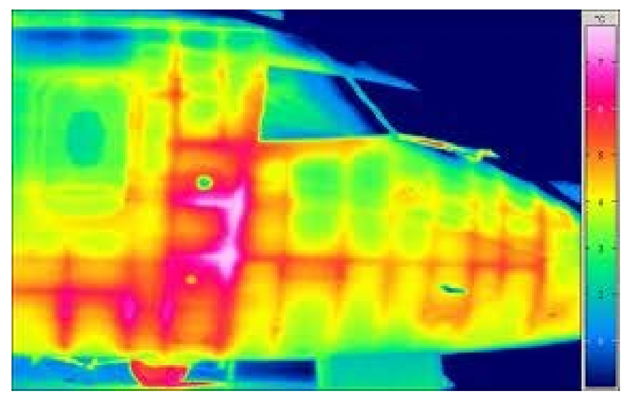
Most NDE techniques are simply *enhanced* forms of visual inspection

Dye Penetrant

Magnet Particle



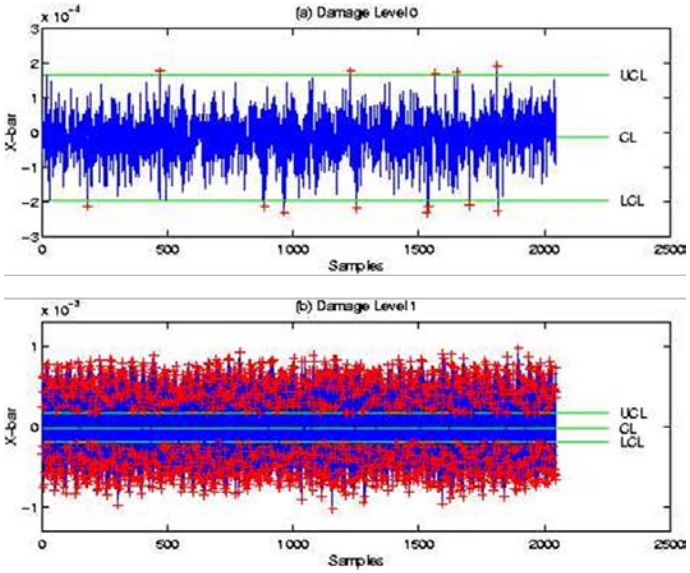
Radiography



Thermography

More Quantitative Methods

- Through the use of more rigorous statistical analysis, SHM methods are becoming more quantitative.
- However, to some degree they are just moving the visual inspection to the computer screen.
- Control Chart for damage detection in a concrete column:



Can We Bring More Senses to the SHM Problem?

- All of us are field-deployed SHM sensing and processing systems!
  - Visual sensing
  - Acoustic sensing (loose parts)
  - Olfactory sensing (leaks)
  - Tactile sensing (feel changes in system thermal & mechanical dynamics)

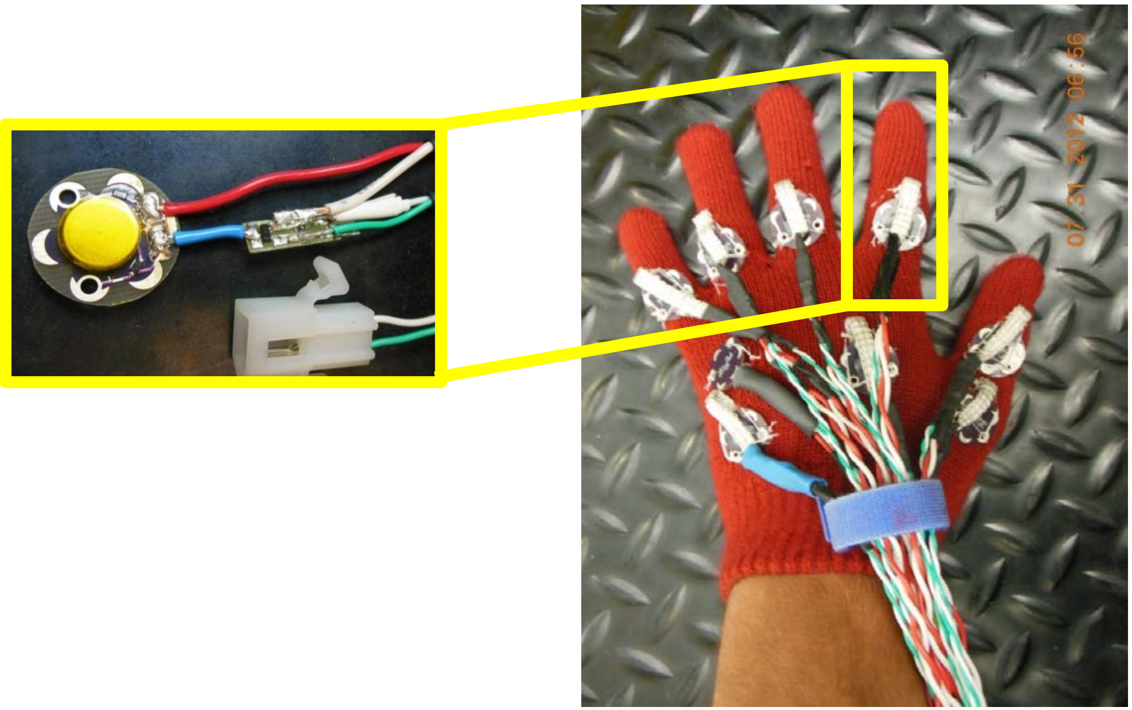
- After an ***appropriate training phase,*** we employ all of these senses to diagnose damage in our cars.

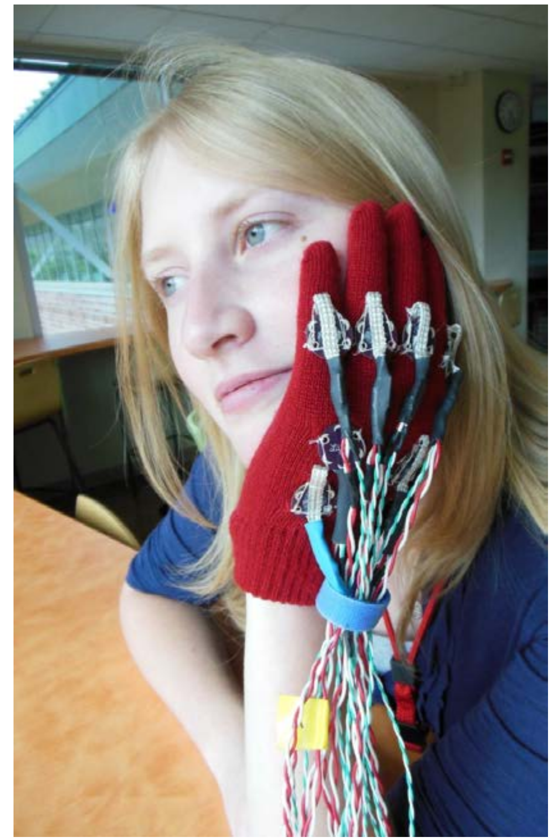
- **How do we engage more "senses" in the SHM process?**

Vibro-Tactile Haptics for Human-Machine Interface

D. Mascareñas, C. Plont, C. Brown, M. Cowell, J. Jameson, J. Block, S. Djidjev, H. Hahn, and C. Farrar, “A vibro-haptic human–machine interface for structural health monitoring,” *International Journal of Structural Health Monitoring* 2014, **13**(6), pp.671-685.

Idea came from TEDtalk: **Shyam Sankar: The rise of human-computer cooperation**





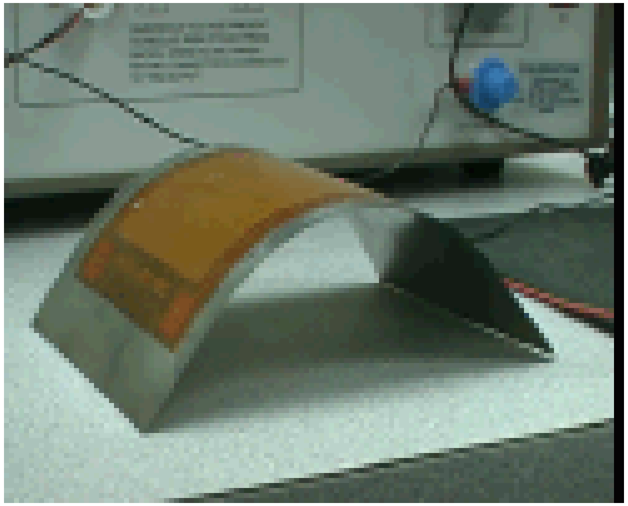
Lots of Question Regarding This New Approach

- How do we best stimulate the human?
  - Amplitude
  - Frequency
  - Location
  - Other senses (audio)
  - Lots of variables
- Who will be wearing the haptic device?
- How long will they wear it?
- How much training is needed?

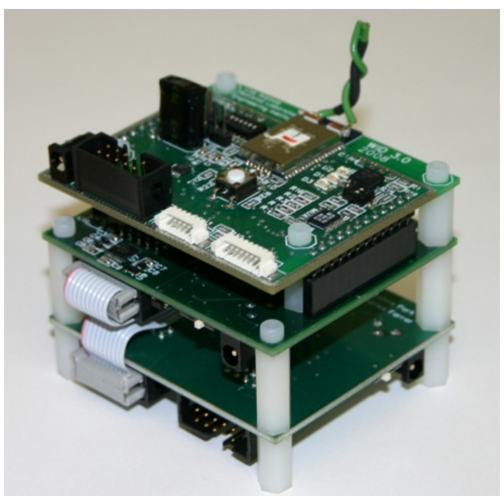
Do we end up with humans in sensory deprivation tanks monitoring our civil infrastructure?

Considerations for SHM Data Acquisition System

- **THERE IS NO SENSOR THAT MEASURES DAMAGE! (and there never will be!!)**
- **However, can't do SHM without sensing**
- Define data to be acquired and the data to be used in the feature extraction process.
  - Types of data to be acquired
  - Sensor types, number and locations
  - Bandwidth, sensitivity (dynamic range)
  - Data acquisition/transmittal/storage system
  - Power requirements (**energy harvesting**)
  - Sampling intervals
  - Processor/memory requirements
  - Excitation source (**active sensing**)
  - **Sensor diagnostics**



LANL/UCSD Wireless Power Delivery



Challenges for SHM Sensing Systems

- **Number of sensors**
  - Large structures with 100s of sensors is still a sparsely instrumented system!
  - Large sensor systems pose challenges for reliability and data management
- **Ruggedness of sensors**
  - Last for years with minimal maintenance
  - Harsh environments
  - **Need sensor diagnostic capability**

Tsing Ma Bridge in Hong Kong (approx. $20 million for 1000+ channels of data acquisition)

- **The sensing system must be developed integrally with the feature selection/extraction and classification.**
- **There is no accepted sensor design methodology**
  - **Optimal (or robust?) sensor system design (need models)**
  - **Optimal waveform design for active sensing (need models)**

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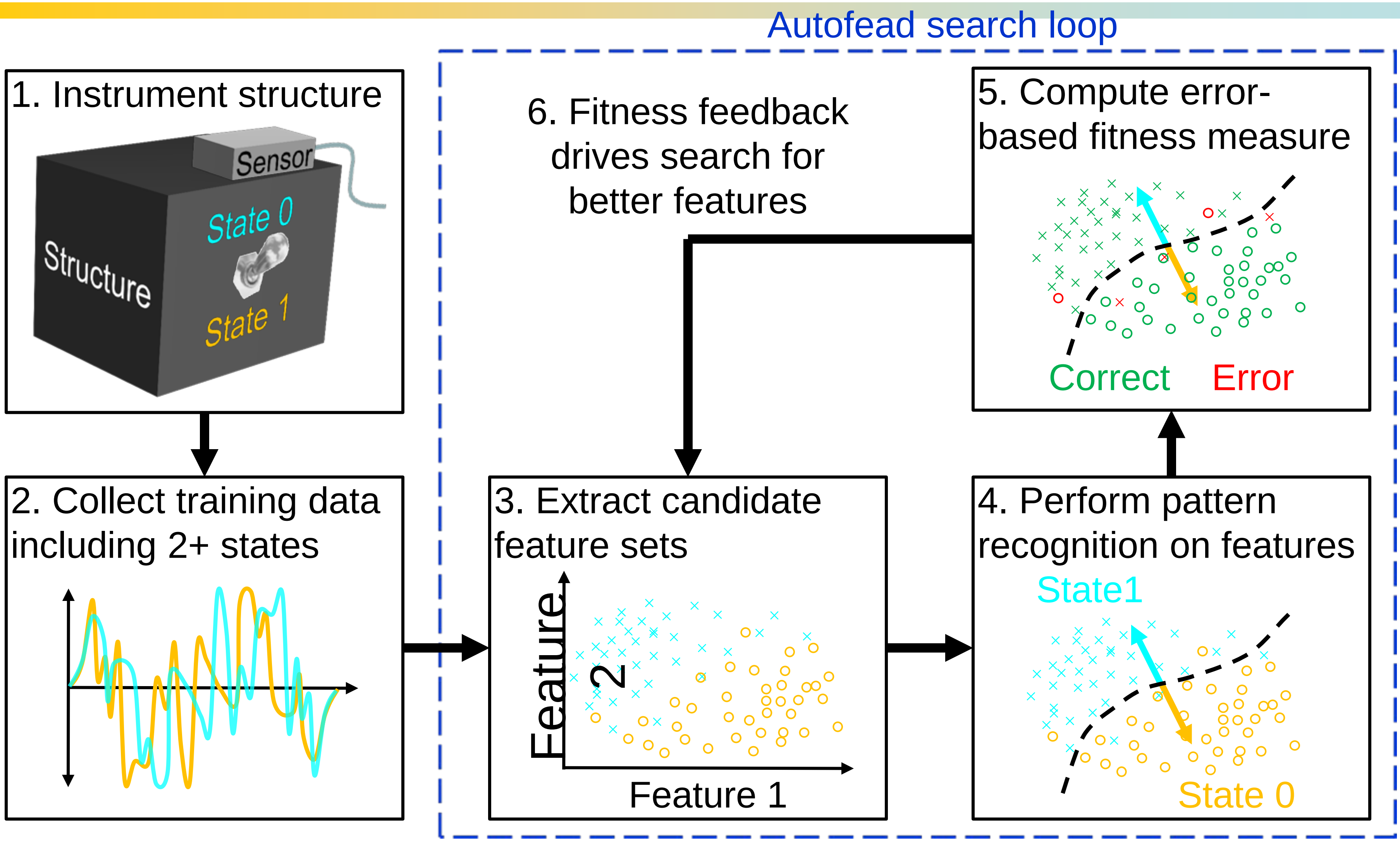
Bayesian Risk Approach to Optimal Sensor System Design
(E. Flynn Ph.D. dissertation, UCSD)

- What are the **relevant damage states, *θ*,** and their **probability** of occurring P(θ)?
  - "Undamaged" / "Damaged", Continuous states: extent, location
- What are the **system costs** associated with the SHM design (*e*)?
  - Hardware cost, Maintenance cost, Operation cost
- What **actions, *d*,** does the SHM/DP system dictate in response to observing a damage state?
  - Continue/reduce/stop operation; Inspect component or entire structure; do nothing
- What are the **costs** of taking each of those response actions?
  - Cost of inspection vs missing damage, detecting damage in the wrong location

$$E(L) = \sum_{\theta,d} L_d(d,\theta) P(d|\theta,e) P(\theta) + L_e(e)$$

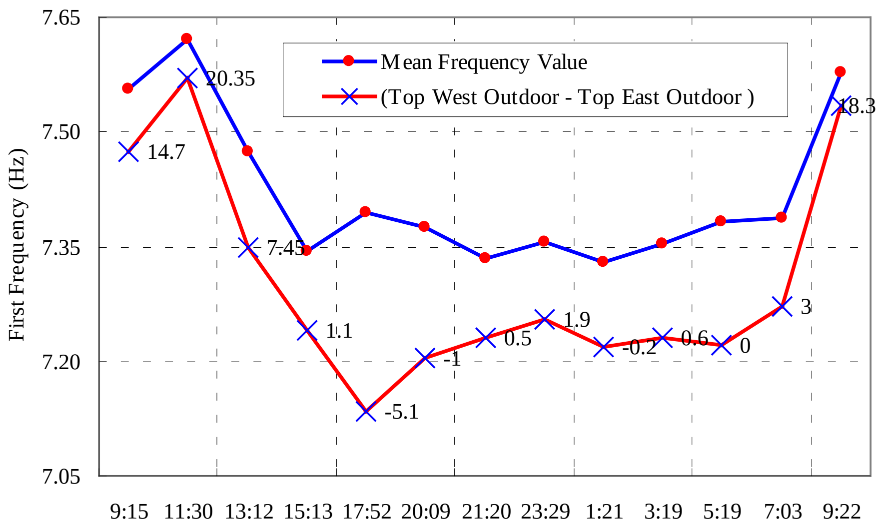
Automated Feature Extraction (D. Harvey, Ph.D. Dissertation, UCSD, "Automated Feature Design for Time Series Classification by Genetic Programming")

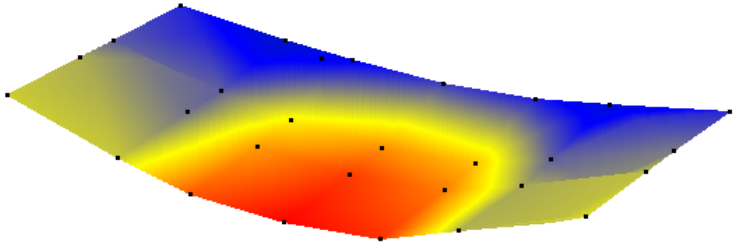


Challenges for Feature Selection and Extraction

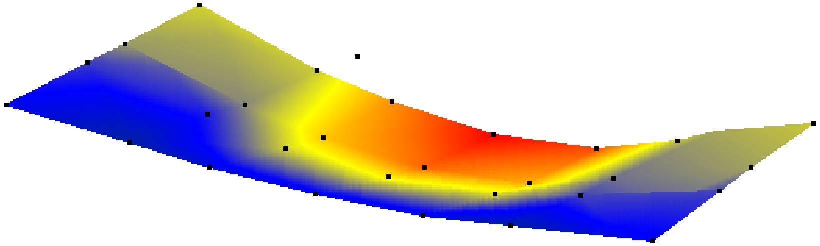
- **Developing an analytical approach to feature selection**.
  - Feature selection is still based almost exclusively on engineering judgment
  - Measures of complexity?
- **Quantifying the features sensitivity to damage**
- **Quantifying how the feature's change with damage level**.
- **Understanding how the feature will change with changing environmental and operational conditions**
  - **The biggest barriers to *in situ* deployment of SHM systems!**

Environmental Variability





First mode, 10 AM



First mode, 5:30 PM

Challenges for Statistical Modeling

- **Analytical approaches to defining threshold levels and to tie thresholds to performance criteria**
  - Must balance tradeoffs between false-positive and false-negative indications of damage.
    - Minimize false-positives when economic concerns drive the SHM application (e.g. wind turbines)
    - Minimize false-negatives when life-safety issues drive the SHM application (e.g. nuclear power plant)
- **Updating statistical models as new data become available**
- **Managing the large volumes of data that will be produced by an on-line monitoring system**
  - **Learn how others do it**
    - **credit card fraud detection**
    - **syndromic surveillance for disease epidemic outbreak**

System Level Challenges for SHM

- **The SHM Catch-22**
  - Owners will not invest in SHM technology until it is demonstrated on a real world system.
  - Real-world structures are generally not available to damage in an effort to develop and demonstrate SHM technology.
- **There is no widely accepted procedure to demonstrate rate-of-return on investment in an SHM/DP system**
- **Need people who can envision the entire lifecycle and who can integrate diverse technologies.**
- **Is education evolving to address the need for more multi-disciplinary technology developers and integrators?**

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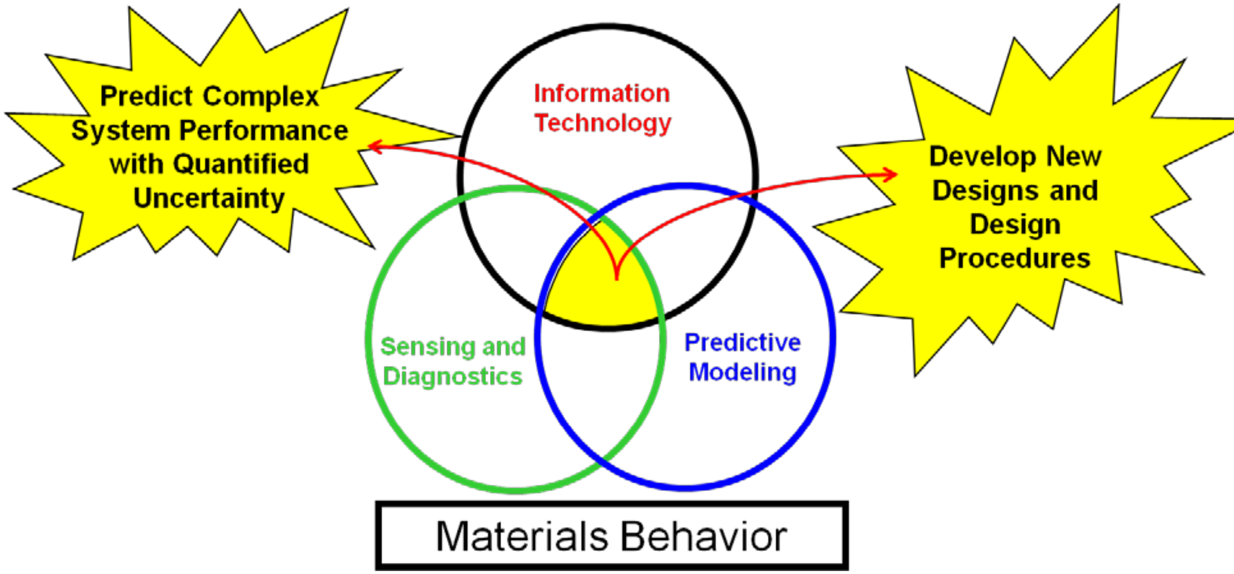
A Vision for Engineering Research: Cognitive, Adaptive, Infrastructure Systems



- Design system functionality in at the material and manufacturing level
- Monitor, assess, and control in-service system condition (SHM)
- Intelligent System Retirement (SHM/DP)

Courtesy of M. Wang, Northeastern Univ.

Bridge SHM Systems in China: Before 2000

No	Year	Name	Type	Locate	Span (m)	Sensors installed*	Total
1	1995	Tongling Yangtze River Bridge	Cable Stayed	Anhui	432	1, 2, 4, 11, 13	
2	1997	TsingMaBridge	Suspension	Hong Kong	1377	1—7, 12, 18	278
3	1997	KapShui Mun Bridge	Cable Stayed	Hong Kong	430	1—7, 12, 18	288
4	1998	TingKauBridge	Cable Stayed	Hong Kong	475	1—7, 12, 18	285
5	1999	Xupu Bridge	Cable Stayed	Shanghai	590	2—4, 7, 12	76

1—anemometers; 2—temperature sensors; 3—strain gauges; 4—accelerometers; 5—displacement transducers; 6—global positioning systems; 7—weigh-in-motion systems; 8—corrosion sensors; 9—elasto-magnetic sensors; 10—optic fiber sensors; 11—tiltmeters; 12—level sensors; 13—total stations; 14—seismometers; 15—barometers; 16—hygrometers; 17—pluviometers; 18—video cameras, 19—joint expansion disp., 20—fatigue gage

Courtesy of M. Wang,
Northeastern Univ.

Bridge SHM Systems in China: 2005

No	Year	Name	Type	Locate	Span (m)	Sensors installed*	Total
14	2005	Jiangyin Bridge (after upgrade)	Suspension	Jiangsu	1385	1—6, 9, 10, 13	185
15	2005	3rd Nanjing Yangtze River Bridge	Cable Stayed	Jiangsu	648	1—5, 10, 11	**1303**
16	2005	Runyang South Bridge	Suspension	Jiangsu	1490	1—4, 6	241
17	2005	Runyang North Bridge	Cable Stayed	Jiangsu	400	1—4	188
18	2005	Wuhu Bridge	Cable Stayed	Anhui	312	2—5, 10, 12	152
19	2005	Donghai Bridge, Main Route	Cable Stayed	Shanghai	420	1—3, 6, 8, 9, 12, 19, 20	266
20	2005	Donghai Bridge, Kezhushan Route	Cable Stayed	Shanghai	332	2—4, 6, 9, 19,20	115
21	2005	Donghai Bridge, Other Approaching Routes	Concrete Girder	Shanghai	70,120, 140,160	2, 12	180
22	2005	Dongying Yellow River Bridge	Cable Stayed	Shandong	300	2, 10	**1868**

2008~2009 courtesy of Zhu Mao,
Univ. of Massachusetts , Lowell

HMS in China

No	Year	Name	Type	Locate	Span (m)	Sensors installed*	Total
1	2008	East Sea Bridge	Cable Stayed	ShangHai	420	1-6, 8	266
2			Cable Stayed	ShangHai	322		115
3	2008	Hongdu Bridge	Suspension	Jiangxi	195	2, 4-6, 21	86
4	2008	Yingxiong Bridge	Cable stayed	Jiangxi	188	2, 3, 5, 6	86
5	2008	Sutong Bridge	Cable Stayed	Jiangsu	1088	1-6, 8-11, 16	1440
6	2009	Balinghe Bridge	Suspension	Guizhou	1088	1-2, 4-7, 10, 11, 14, 16, 18, 19, 21	256
7	2009	Bayi Bridge	Cable stayed	Jiangxi	160	2, 5-7, 10, 18, 21	223
8	2009	Yingzhou Bridge	Arch	Henan	610	2-5, 10	176

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2010~2011courtesy of Zhu Mao,
Univ. of Massachusetts, Lowell

HMS in China

No	Year	Name	Type	Locate	Span (m)	Sensors installed*	Total
9	2010	Jiubao Bridge	Arch	Zhejiang	210	1, 2, 4, 5, 7, 10, 14, 16, 18, 19, 21	333
10	2010	Songpu Bridge	Cable stayed	Heilongjiang	268	1-3, 5, 10, 11, 16, 19, 21	209
11	2010	Lijiatuo YangtzeRiver Bridge	Cable Stayed	Chongqing	444	2-5, 11, 18, 19	231
12	2011	Junshan YangtzeRiver Bridge	Cable Stayed	Hubei	460	1, 2, 4, 6, 7, 10, 11, 14, 16, 19	349
13	2011	Erqi Yangtze River Bridge	Cable Stayed	Hubei	616	1, 2, 4, 6, 7, 10, 11, 14, 16, 18, 19, 21	380
14	2011	Dongjiang Bridge	Suspension	Guangdong	208	1, 2, 4, 6, 7, 10, 11, 14, 16, 17, 19	365
15	2011	Shuangyong Bridge	Suspension	Guangxi	510	2-5, 16, 21	109
16	2011	Si Du He Bridge	Suspension	HuBei	900	1, 2, 4, 5-7, 10, 11	252
17	2011	Tie Luo Ping Bridge	Cable Stayed	HuBei	322	1, 2, 4-6, 10	296
18	2011	Zhi Jing He Bridge	Arch	HuBei	420	2, 4, 10,11	208

1—anemometers; 2—temperature sensors; 3—strain gauges; 4—accelerometers; 5—displacement transducers; 6—global positioning systems; 7—weigh-in-motion systems; 8—corrosion sensors; 9—elasto-magnetic sensors; 10—optic fiber sensors; 11—tiltmeters; 12—level sensors; 13—total stations; 14—seismometers; 15—barometers; 16—hygrometers; 17—pluviometers; 18—video cameras; 19—joint expansion disp., 20—fatigue

2012 courtesy of Zhu Mao, Univ. of California, San Diego

HMS in China

No	Year	Name	Type	Locate	Span (m)	Sensors installed*	Total
19	2012	Fenghua River Bridge	Arch	Zhejiang	260	1-4, 6-7, 10, 11, 14, 16, 19, 21	360
20	2012	Hanjiatuo Yangtze River Bridge	Cable Stayed	Chongqing	432	1, 2, 4, 5, 11, 21	93
21	2012	Fulin Yangtze River Bridge	Cable Stayed	Chongqing	330	2, 4, 5, 11, 16, 19	70
22	2012	Yingwuzhou Yangtze River Bridge	Suspension	Hubei	850	1-4, 6, 10, 11, 14, 16, 19	219
23	2012	Langqi Ming River Bridge	Cable Stayed	Fujian	680	1, 2, 4, 6, 7, 10, 11, 14, 16, 19	222
24	2012	Sixth Jianghan Bridge	Suspension	Hubei	252	1-4, 10, 11, 16, 19, 21	176
25	2012	Ma'anshan Yangtze River Bridge	Suspension	AnHui	1080	1, 2, 4, 5, 6, 10, 11, 16	442
26			Cable Stayed	AnHui	260		
27	2012	Taizhou Yangtze River Bridge	Suspension	Jiangsu	1080	1-4, 6,16	275

1—anemometers; 2—temperature sensors; 3—strain gauges; 4—accelerometers; 5—displacement transducers; 6—global positioning systems; 7—weigh-in-motion systems; 8—corrosion sensors; 9—elasto-magnetic sensors; 10—optic fiber sensors; 11—tiltmeters; 12—level sensors; 13—total stations; 14—seismometers; 15—barometers; 16—hygrometers; 17—pluviometers; 18—video cameras, 19—joint expansion disp., 20—fatigue

2013-2014 courtesy of Zhu Mao, Univ. of Massachusetts, Lowell

HMS in China

No	Year	Name	Type	Locate	Span (m)	Sensors installed*	Total
28	2013	Guojiahuayuan Bridge	Concrete Girder	Chongqing	240	2, 3, 5, 7	94
29	2013	Guozigou Bridge	Cable Stayed	XinJiang	360	1, 2, 4-7, 10, 11, 16	277
30	2014	Dongshuimen Yangtze River Bridge	Cable Stayed	Chongqing	445	1-7, 16, 18, 19	208
31	2014	Qiansimen Yangtze River Bridge	Cable Stayed	Chongqing	312	1-7, 16, 18, 19	175

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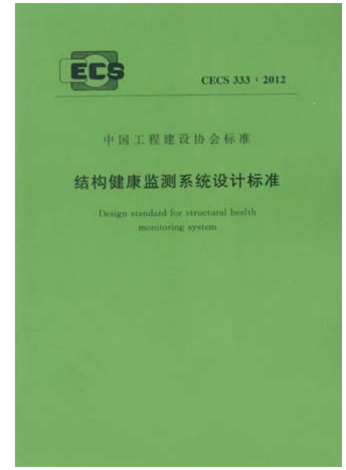
SHM Standards in China

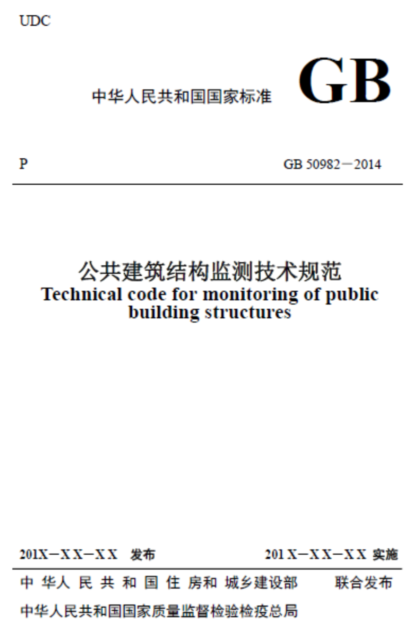
Design Standard for Structural health Monitoring systems
(CECS 333:2012)

by the **China Project Construction Association**



Technical code for monitoring of public building structures (GB 50982－2014**)** -to be implemented

by the **Ministry of Housing and Urban-Rural Development of China**,
and
the **General Administration of Quality Supervision, Inspection and Quarantine of China**



UDC

中华人民共和国国家标准 GB

P GB 50982—2014

公共建筑结构监测技术规范
Technical code for monitoring of public building structures

201X—XX—XX 发布 201X—XX—XX 实施

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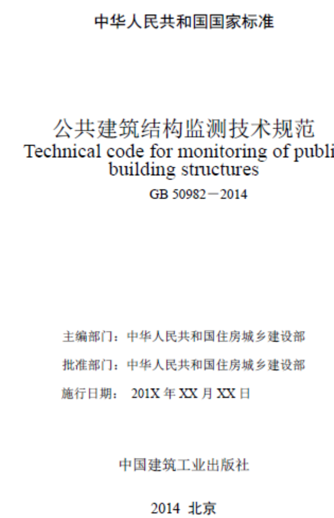

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Technical code for monitoring of public building structures
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施行日期： 201X 年 XX 月 XX 日

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2014 北京

Bridge SHM Systems in China

China leads in:

Quantity: Since 2005, almost all major new bridges as well as some old bridges have SHM systems. Currently estimated more than 40 systems.

Scale: From simple to complex, largest systems contains 1000+ sensors for one bridge. On the order of 0.6% of construction cost

Quality: Some systems have been deployed for 10+ years, but the many are relatively new.

Technology used: Distributed network, remote access, substation, fiber optical, and other new sensor technologies.

Some of Our Team

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