UNIVERSIDAD DE GRANADA

Máster Universitario en Estructuras
Curso 2020-2021

Tema I: Análisis modal dentro del marco del mantenimiento de la salud estructural

Módulo: MÓDULO FUNDAMENTAL: CALIDAD Y DAÑO
Materia: **Análisis Modal y Detección de Defectos**

Enrique García Macías
enriquegm@ugr.es
Departamento de Mecánica de Estructuras e Ingeniería Hidráulica

Desarrollo del curso

		FECHA		HORA	PROFESOR	TEMA	
Clase 1	**Lunes**	**1**	**febrero**	**9:30-11:30**	**EGM**	**1**	**Introducción: Análisis modal dentro del marco del mantenimiento de la salud estructural.**
Clase 2	Lunes	8	febrero	9:30-11:30	EGM	2	Fuentes de deterioro, patologías estructurales, y tecnologías de monitorización.
Clase 3	Lunes	15	febrero	9:30-11:30	EGM	3	Taller: procesamiento de señales.
Clase 4	Lunes	22	febrero	9:30-11:30	EGM	4	Análisis modal experimental.
Clase 5	Lunes	15	marzo	9:30-11:30	EGM	5	Análisis modal operacional.
Clase 6	Lunes	12	abril	9:30-11:30	EGM	6	Análisis modal operacional automatizado. Práctica de labotatorio I.
Clase 7	Lunes	19	abril	9:30-11:30	EGM	7	Taller: Identificación del daño estructural.
Clase 8	Lunes	26	abril	9:30-11:30	RCT	8	Técnicas de identificación dinámica basadas en análisis modal operacional.
Clase 9	Lunes	26	abril	12:00-14:00	RCT	9	Práctica de laboratorio II: Test de vibración ambiental.
Clase 10	Martes	27	abril	9:30-11:30	RCT	10	Casos de estudio.
Clase 11	Martes	27	abril	12:00-14:00	RCT		Presentación de trabajos.

ENTREGA DE TRABAJOS Y EVALUACIÓN Del 3 al 28 de mayo

ÍNDICE

- ❑ Introducción al paradigma del mantenimiento de la salud estructural.
- ❑ Historia del SHM.
- ❑ Motivaciones y retos del SHM.
- ❑ Análisis modal como técnica revolucionaria dentro del SHM.

Introducción al paradigma del mantenimiento de la salud estructural.

Structural Health Monitoring (SHM)

*The process of implementing a **damage identification** strategy for aerospace, civil and mechanical engineering infrastructure is referred to as Structural Health Monitoring (SHM) [1].*

*SHM is the integration of sensing and possibly also actuation devices to allow the loading and damaging conditions of a structure to be **recorded**, **analyzed**, **localized**, and **predicted** in a way that **nondestructive testing** (NDT) becomes an integral part of the structure and a material [2].*

[1] Farrar, C. R., & Worden, K. (2006). An introduction to structural health monitoring. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1851), 303-315.

[2] Boller, C., Chang, F. K., & Fujino, Y. (Eds.). (2009). *Encyclopedia of structural health monitoring*. Wiley.

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*An **automated** process to conduct **non-destructive** damage **diagnosis**, **localization**, and **prognosis** of **structures**.*

[1] Farrar, C. R., & Worden, K. (2006). An introduction to structural health monitoring. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1851), 303-315.

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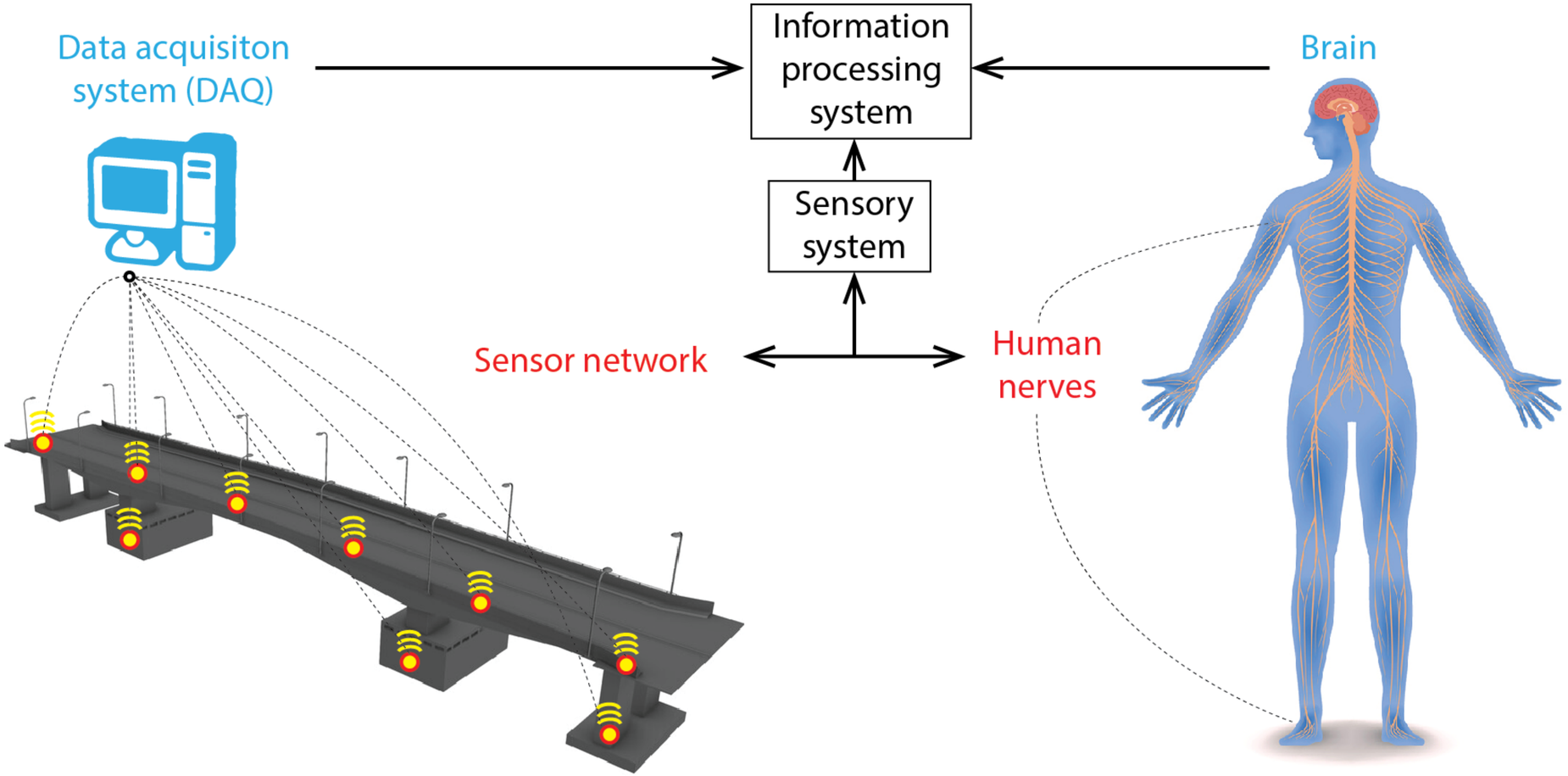
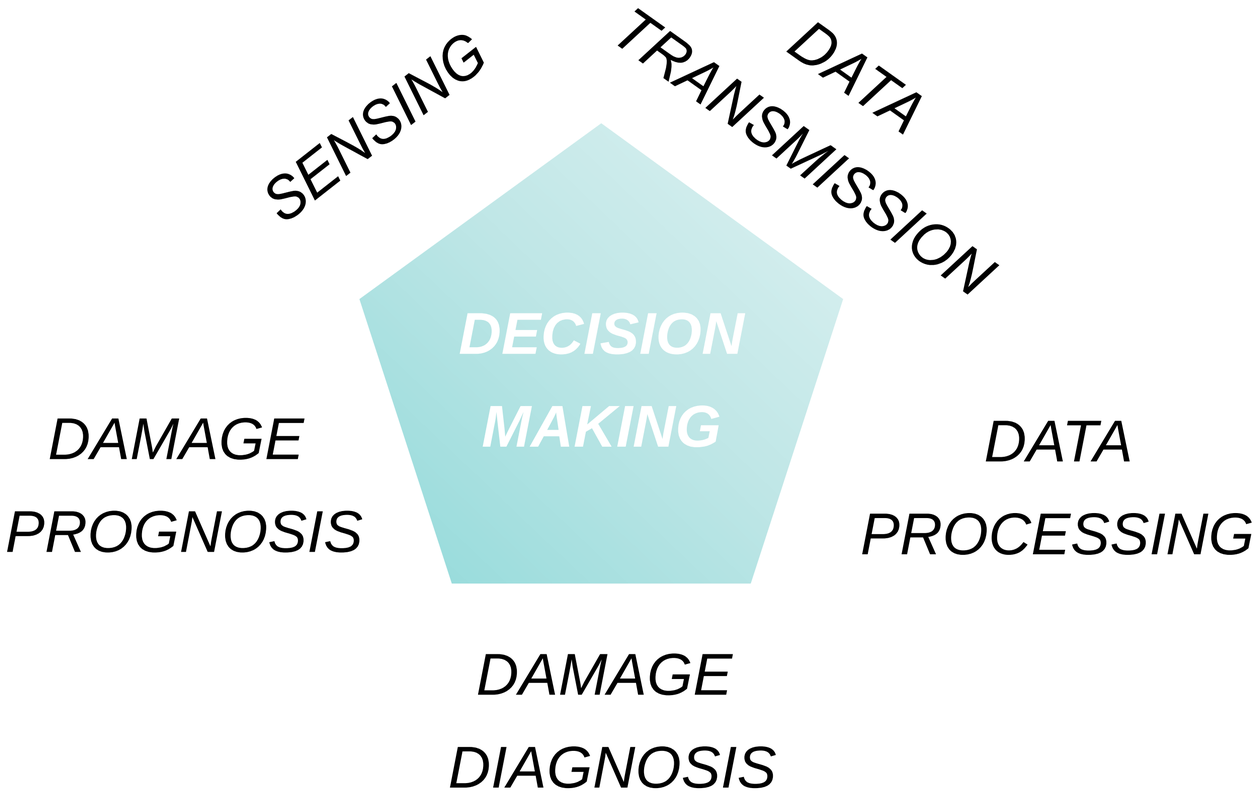
Introducción al paradigma del mantenimiento de la salud estructural

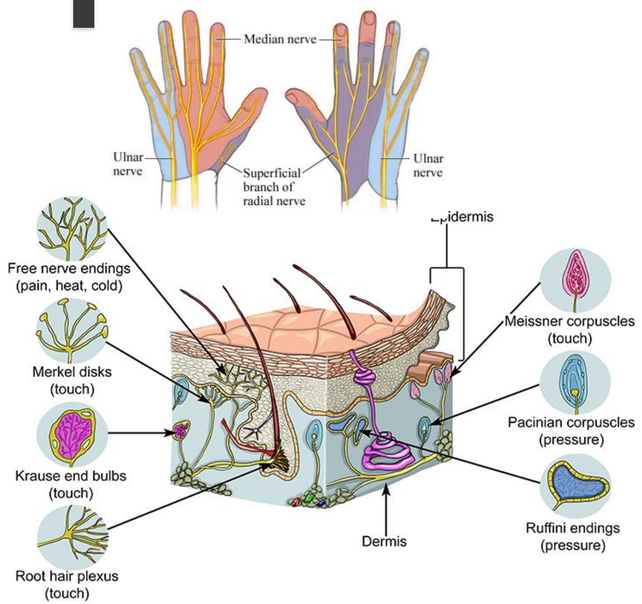


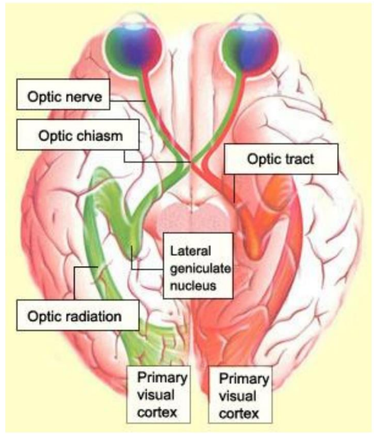
Introducción al paradigma del mantenimiento de la salud estructural

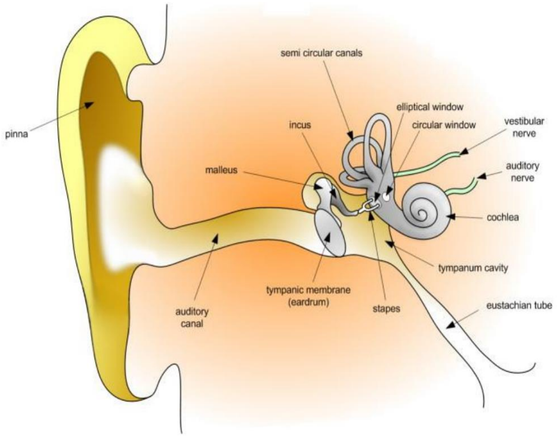


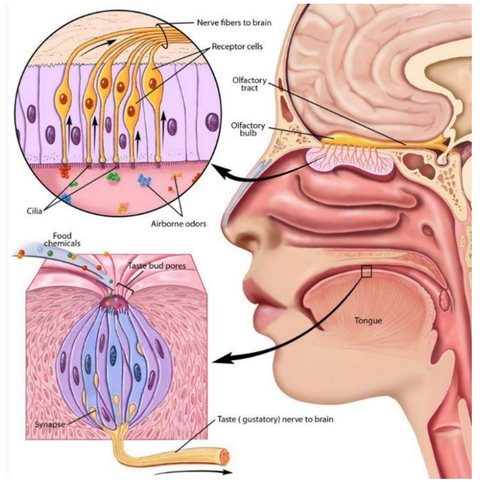
Introducción al paradigma del mantenimiento de la salud estructural

SENSING









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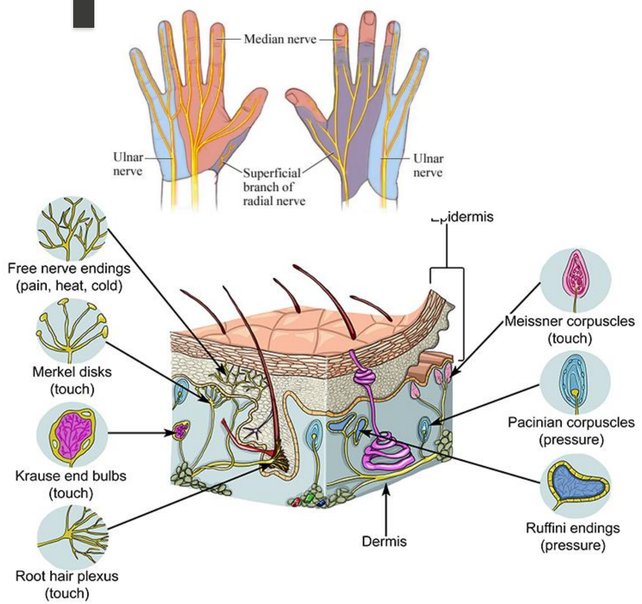
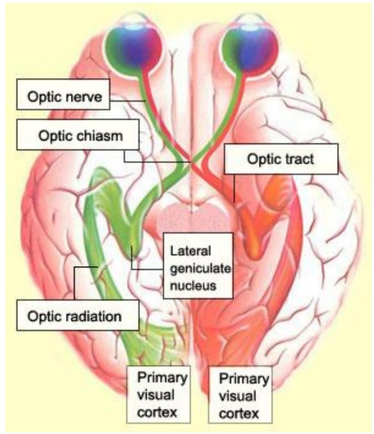
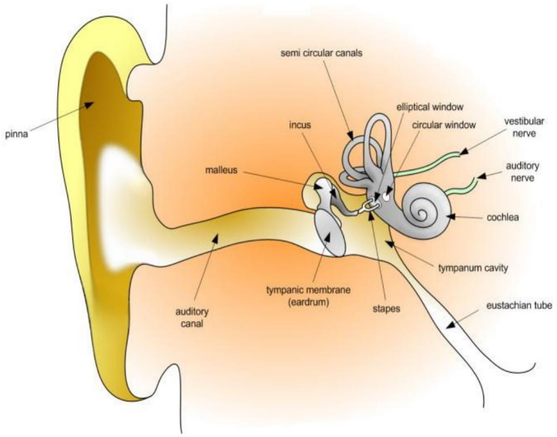
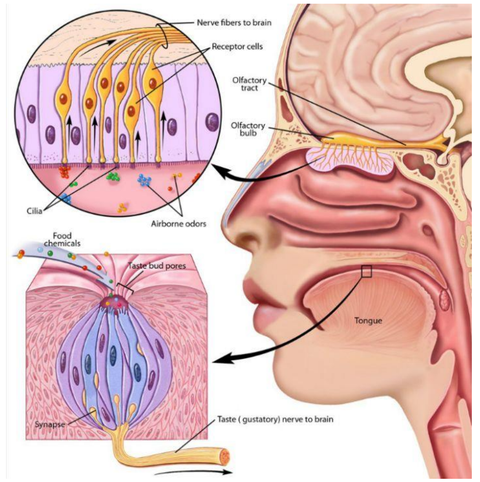




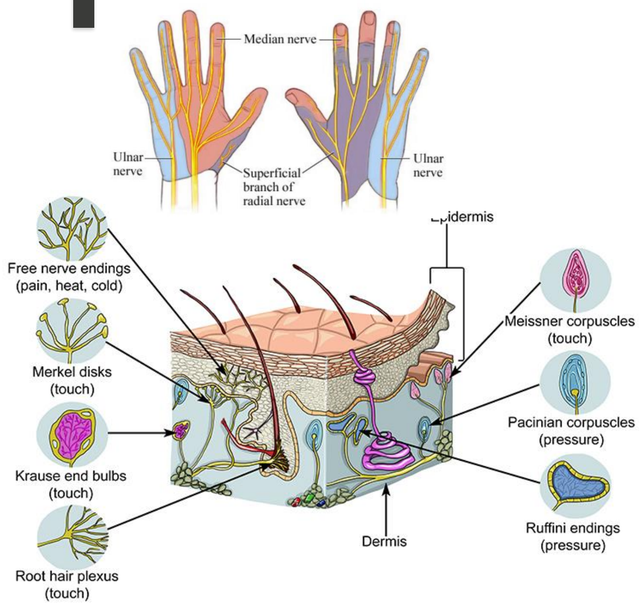


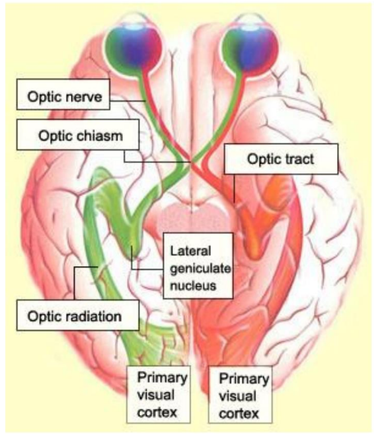


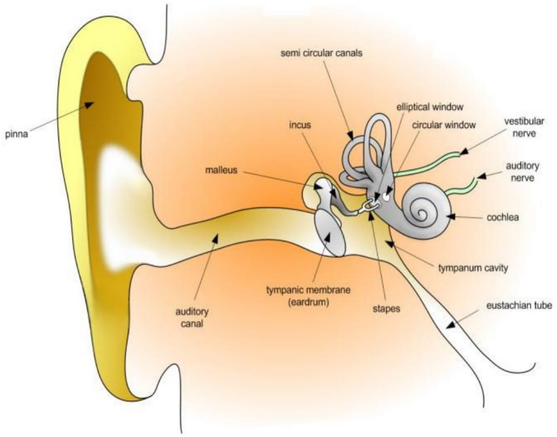
- *Long-term/permanent*
- *Automated*
- *Aggregated (it combines heterogeneous sensing solutions)*

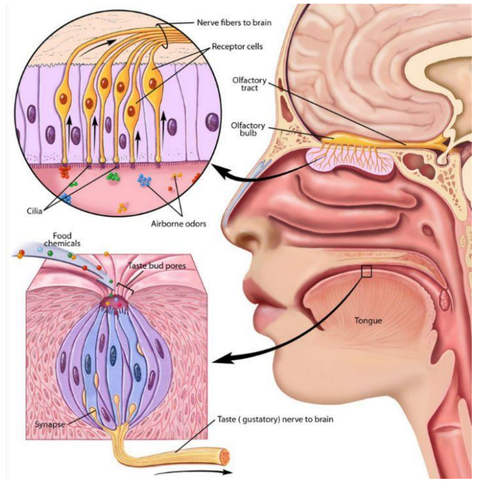
Introducción al paradigma del mantenimiento de la salud estructural

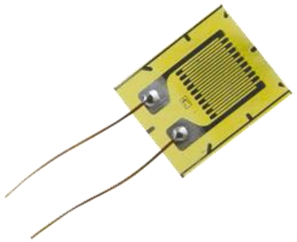
SENSING

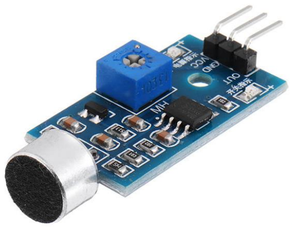


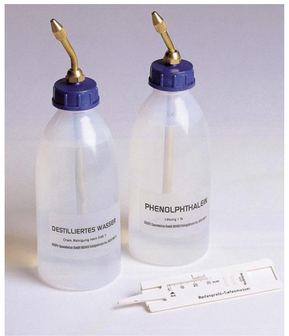








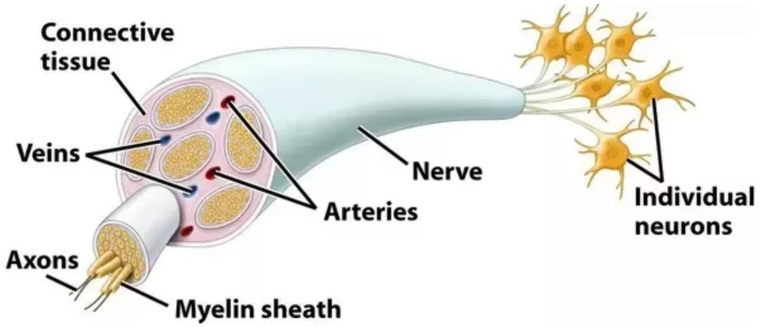


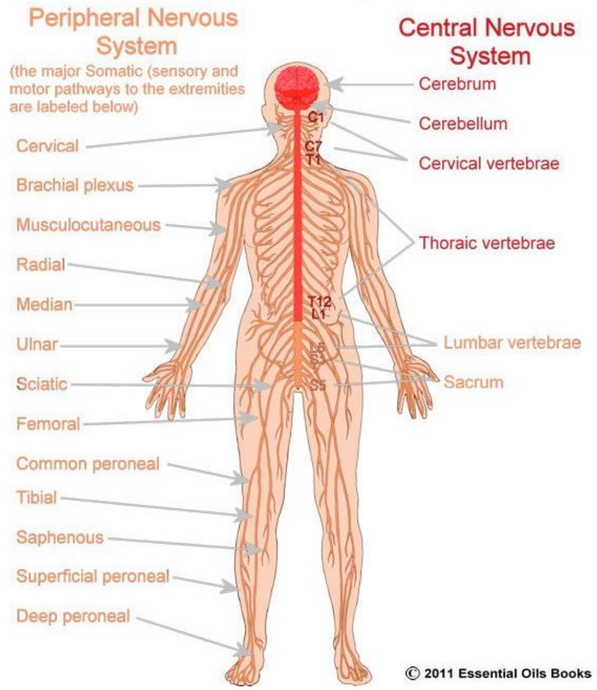


UNIVERSIDAD DE GRANADA

Introducción al paradigma del mantenimiento de la salud estructural

DATA TRANSMISSION





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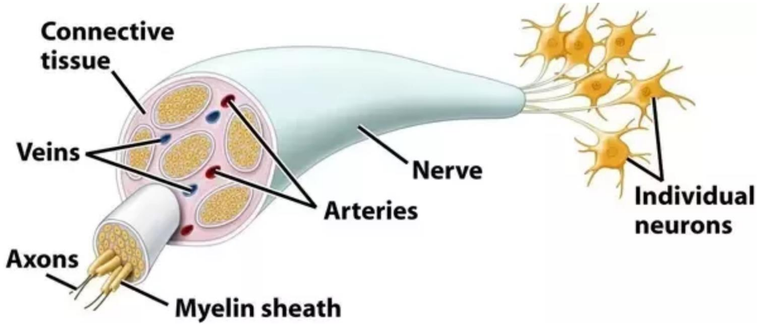

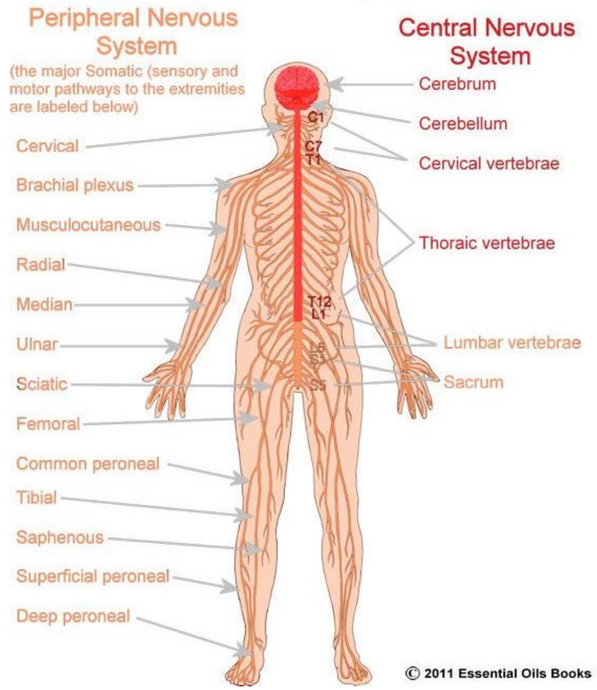

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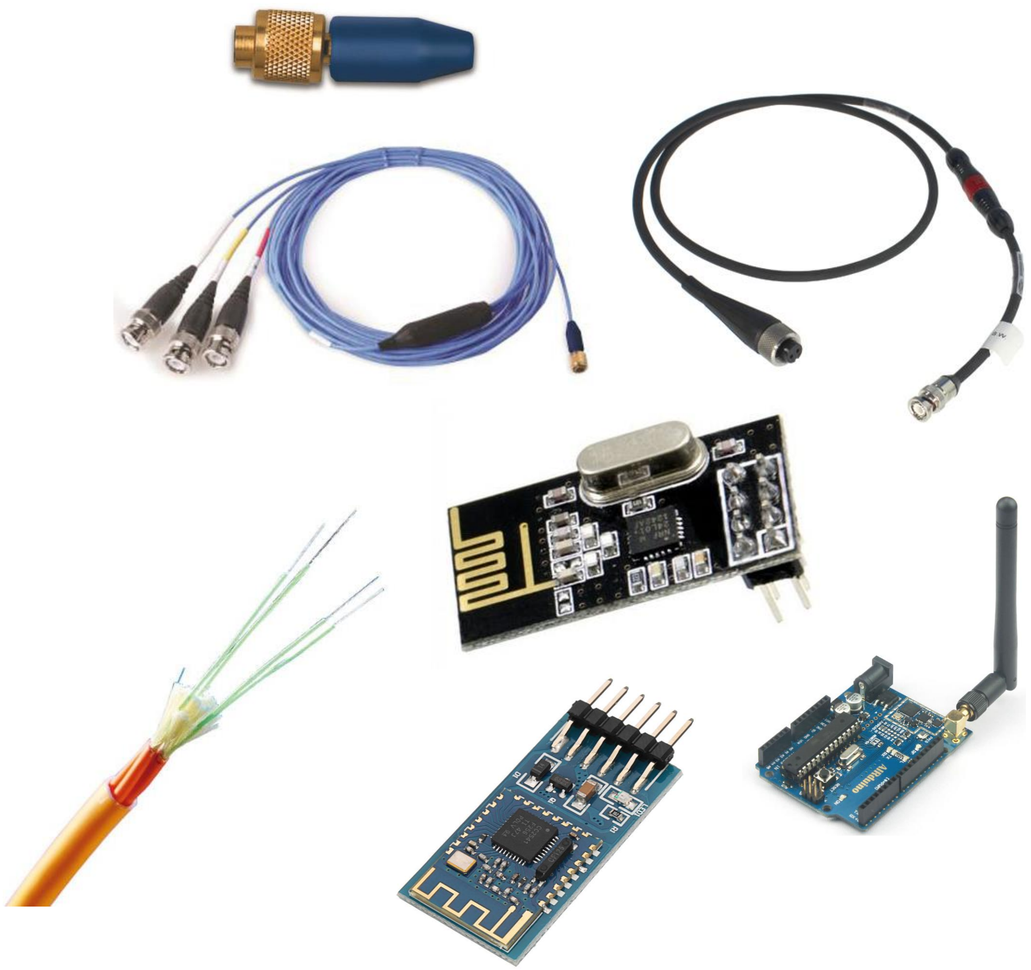
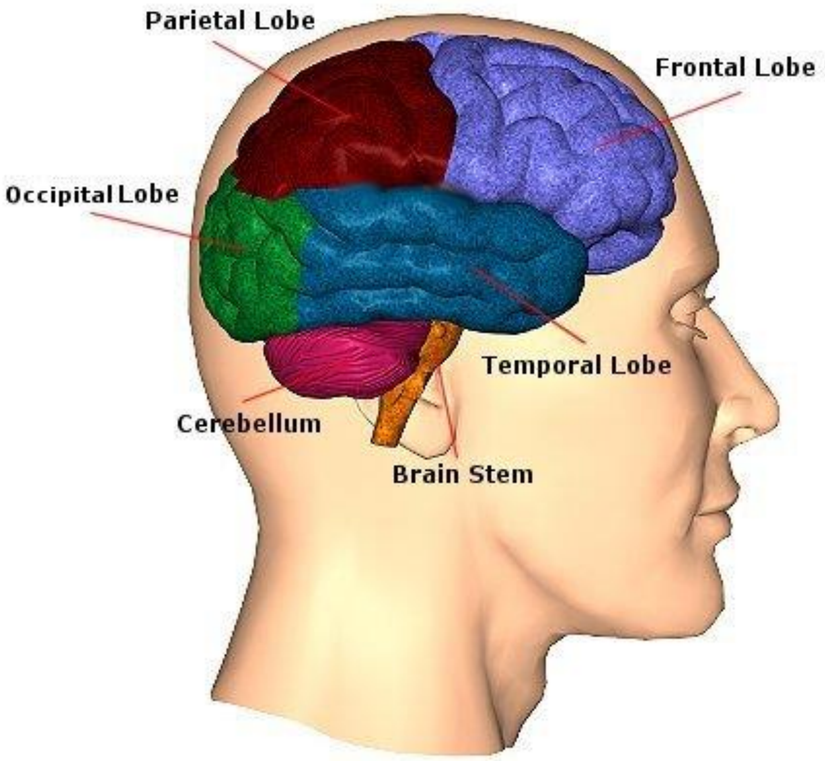


Introducción al paradigma del mantenimiento de la salud estructural

DATA ACQUISITION (DAQs)



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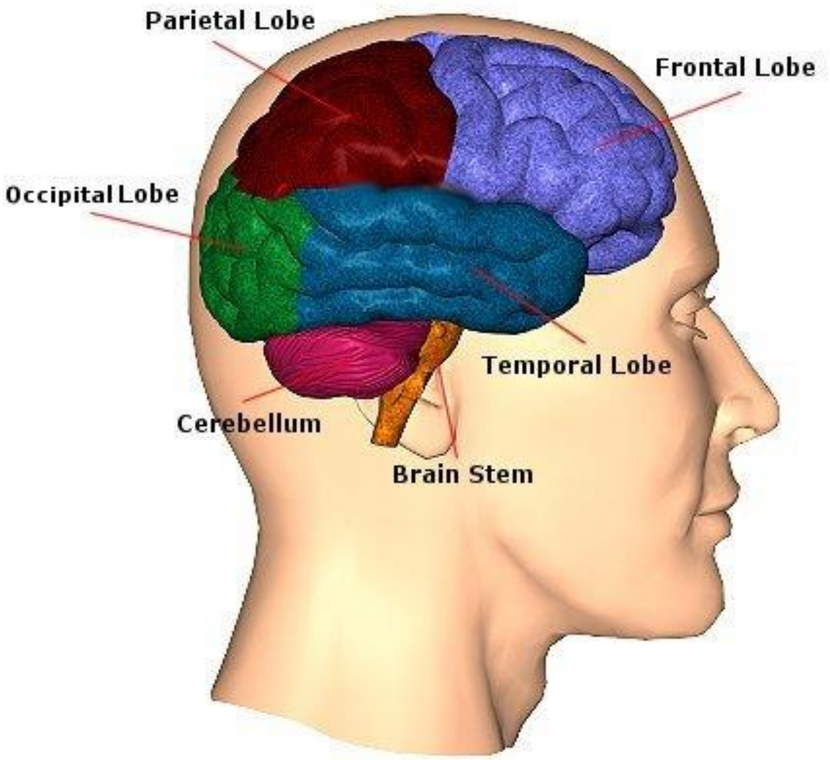
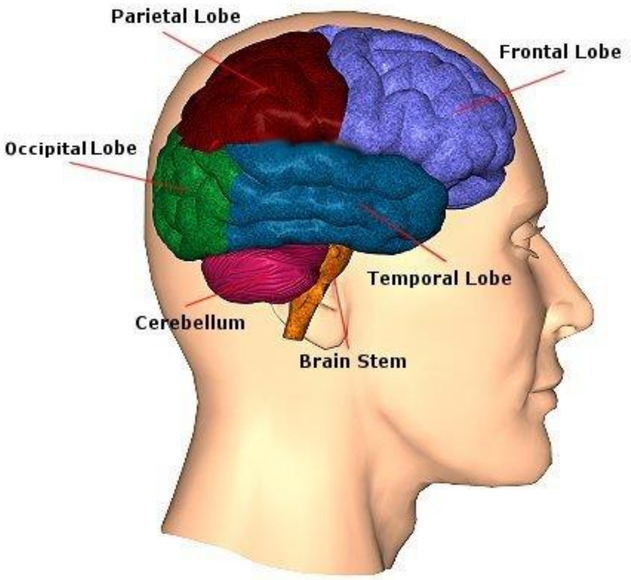


DATA ACQUISITION (DAQs)

6

Introducción al paradigma del mantenimiento de la salud estructural

DIAGNOSIS, PROGNOSIS, DECISION-MAKING

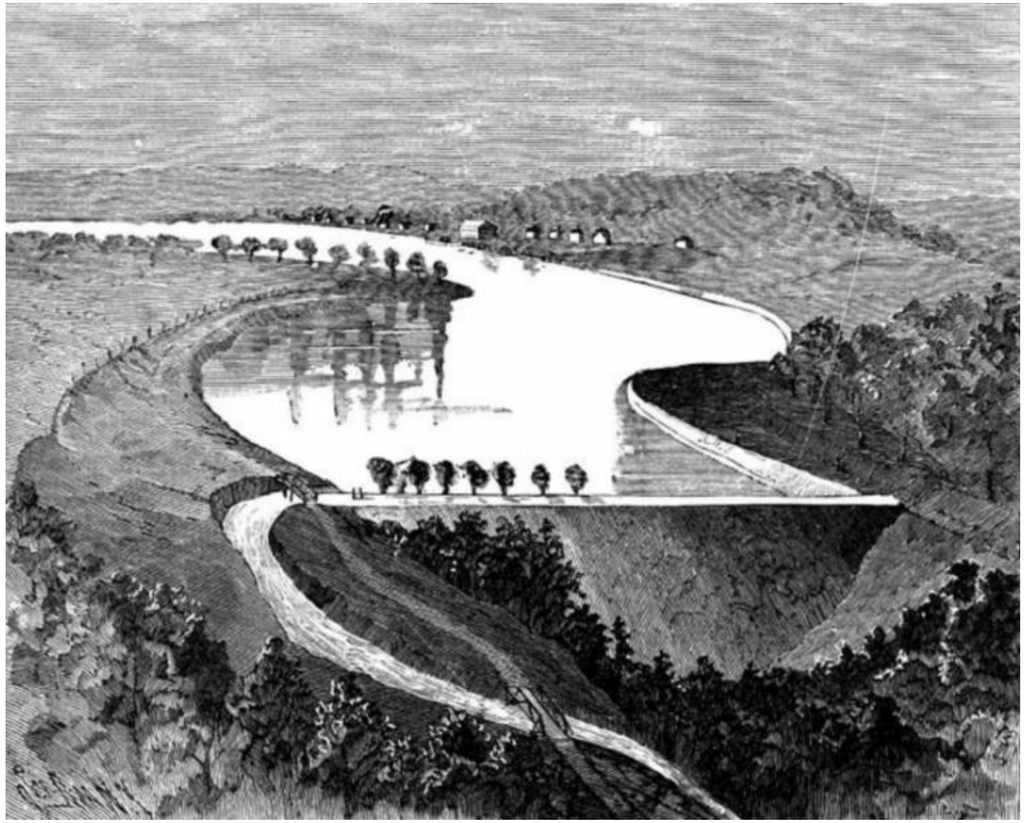


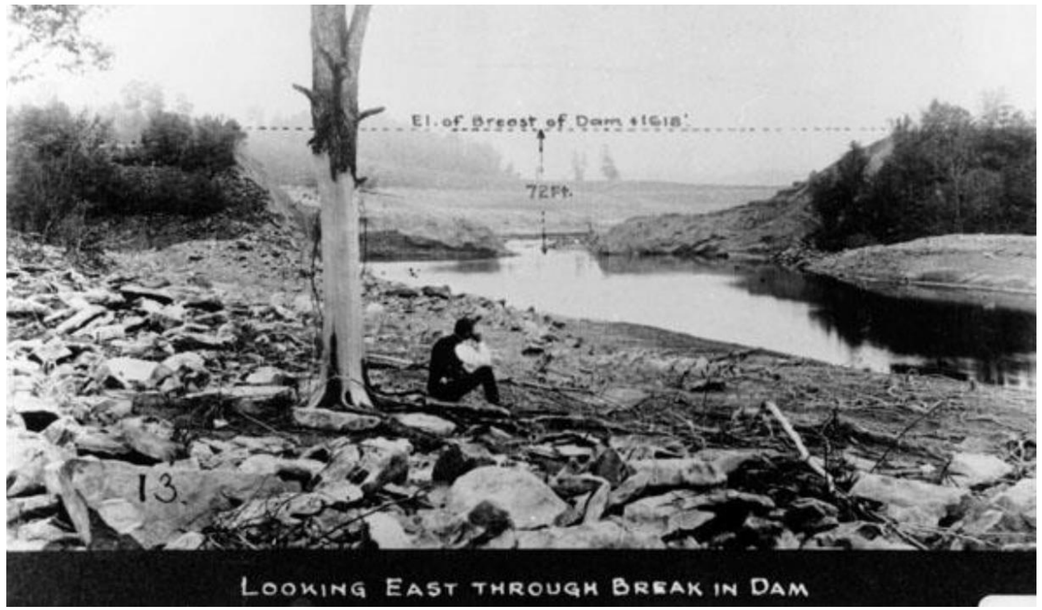
- *Diagnosis*
- *Prognosis*
- *Decision-making*

Historia del SHM.

Historia del SHM

South Fork Dam - The Johnstown Flood (1889)





Historia del SHM

Tacoma Narrows, WA (1940)

https://www.youtube.com/watch?v=3mclp9QmCGs

Historia del SHM

Clifton Bridge (2015)

https://www.youtube.com/watch?v=4we-3tpIppw

Nürnbergs stadium (2016)

https://www.youtube.com/watch?v=X50qwgBuXpY

Historia del SHM

Kobe (1995)

Historia del SHM

L’Aquila (2009)

Historia del SHM

Morandi Bridge collapse (2018)

Historia del SHM

FRANCE 24 LIVE

#IRAN #IMPEACHMENT FRANCE AFRICA CULTURE TV SHOWS FIGHT THE FAKE

Europe

Genoa bridge collapse sounds the alarm on aging infrastructure in Europe

Issued on: 17/08/2018 - 19:24 Modified: 18/08/2018 - 16:55

Piero Cruciatti, AFP | This general view taken on August 15, 2018, shows abandoned vehicles on the Morandi motorway bridge after a section collapsed in the northwestern Italian city of Genoa.

Motivaciones y retos del SHM.

Motivaciones y retos del SHM

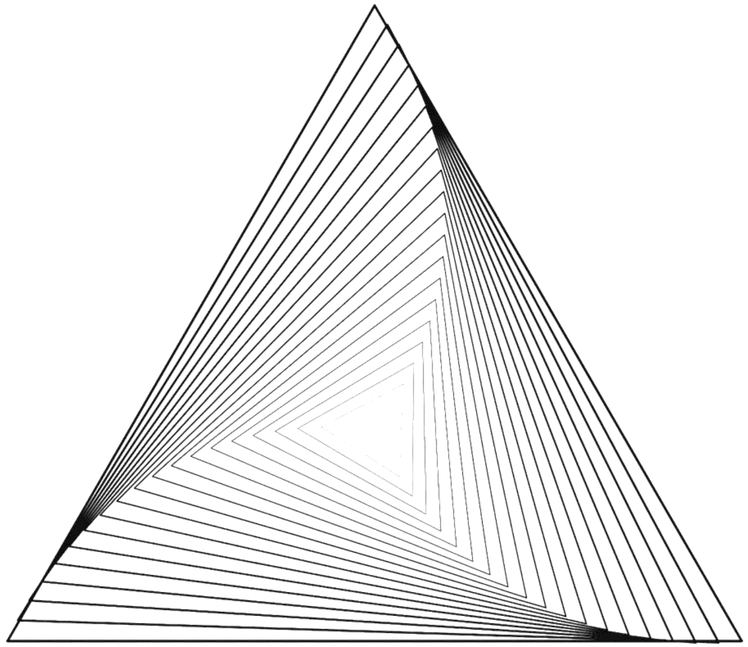
¿Cuáles son las motivaciones para implementar un sistema SHM?

Motivaciones y retos del SHM

- Performance based design can be undertaken by recording site-specific environmental conditions such as wind, load demands or temperature.
- Design assumptions and parameters can be validated with the potential benefit of improving design specifications and guidelines for future similar structures.
- Inspections can be scheduled on an “as needed” basis informed by structure-specific data when indicated by monitoring data.
- Performance thresholds can be established to provide warning when prescribed limits are violated, such as for anomalies in loading and response.
- Real-time safety assessment can be carried out during normal operations or immediately after disasters and extreme events.
- Accuracy of in-situ inspections can be improved by analysing recorded structural response data.
- More accurate information can be used for optimally scheduling maintenance and repair activities, leading to cost savings.

Motivaciones y retos del SHM

- Improving safety.
- Automating inspections.
- Data for improving designs.



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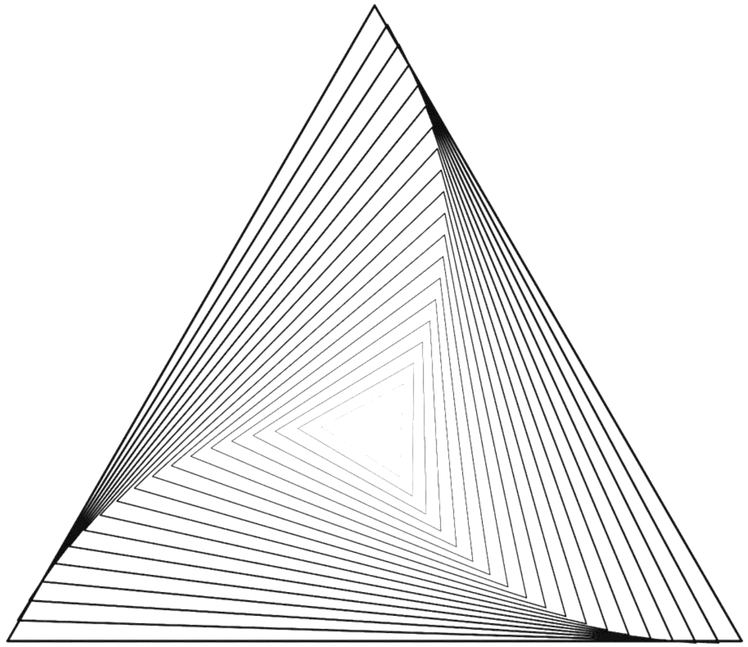


Motivaciones y retos del SHM

Improving safety: optimal use of structures, a minimized downtime, and the avoidance of catastrophic failures.

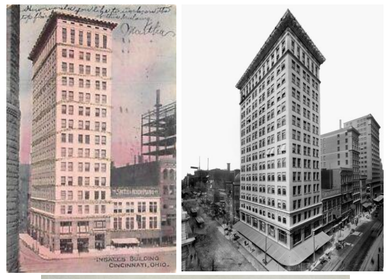
Aloha Airlines Flight 243 (Boeing 737) (1988)

I-95's Mianus River Bridge collapse, Greenwich, Connecticut (1983)

Motivaciones y retos del SHM

- 1853 – The French industrialist François Coignet built the first reinforced concrete structure, a four-story house in Paris.

- 1875 – Joseph Monier built the first reinforced concrete bridge, the Chazalet Bridge (14 meters long span).



- 1903 – Ingalls Building. The world's first reinforced concrete skyscraper (16-story building, 54 meters tall, USA).

- 1936 – Franz Dischinger designed the first post-tensioned concrete bridge (Aue/Saxony).

- 1938 - Eugène Freyssinet built the first pre-stressed concrete bridge (Algeria)
- 1940 - Oelde Bridge (Germany)

Motivaciones y retos del SHM

2017 INFRASTRUCTURE REPORT CARD

2017 INFRASTRUCTURE REPORT CARD ASCE

Bridges C+

9.1% of bridges rated structurally deficient

SUMMARY

The U.S. has 614,387 bridges, almost four in 10 of which are 50 years or older. 56,007 — 9.1% — of the nation's bridges were structurally deficient in 2016, and on average there were 188 million trips across a structurally deficient bridge each day. While the number of bridges that are in such poor condition as to be considered structurally deficient is decreasing, the average age of America's bridges keeps going up and many of the nation's bridges are approaching the end of their design life. The most recent estimate puts the nation's backlog of bridge rehabilitation needs at $123 billion.

RAC Foundation

Bridge maintenance backlog grows

07 Jan 2019

£6.7 billion needed to clear workload

Analysis by the RAC Foundation of data for the 2017-18 financial year shows that an estimated £6.7 billion is needed to carry out all the work that would be required on the tens of thousands of local authority bridges (defined as structures over 1.5m in span).

NACE INTERNATIONAL

Corrosion Costs by Industry Sector

The U.S. economy was divided into five major sector categories for analysis in the corrosion cost study, and these were further broken down into 26 sectors. The categories were infr... production and manu... added together, the to... sectors was $137.9 bi... extrapolated to the to... an annual cost of cor...

tion materials. Approximately 15% of these bridges are structurally deficient because of corroded steel and steel reinforcement. Annual direct cost estimates total $8.3 billion, including $3.8 billion to replace deficient bridges over the next 10 years, $2 billion for main-

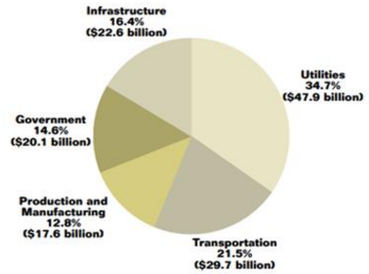
Infrastructure

The aging infrastructure ... the most serious problems ... society today. In past decades, corrosion professionals focused primarily on new construction—specifying materials and designing corrosion prevention and control systems for buildings, ... designed lifetime, the emphasis is on maintaining and extending the life of these valuable assets.

Infrastructure in this study was divided into the following sectors: highway bridges, gas and liquid transmission pipelines, waterways and ports, hazardous materials storage, airports, and railroads. The annual direct cost in this category was estimated to be $22.6 billion (Figure 2).

FIGURE 1

COST OF CORROSION IN INDUSTRY CATEGORIES ($137.9 BILLION)



HIGHWAY BRIDGES

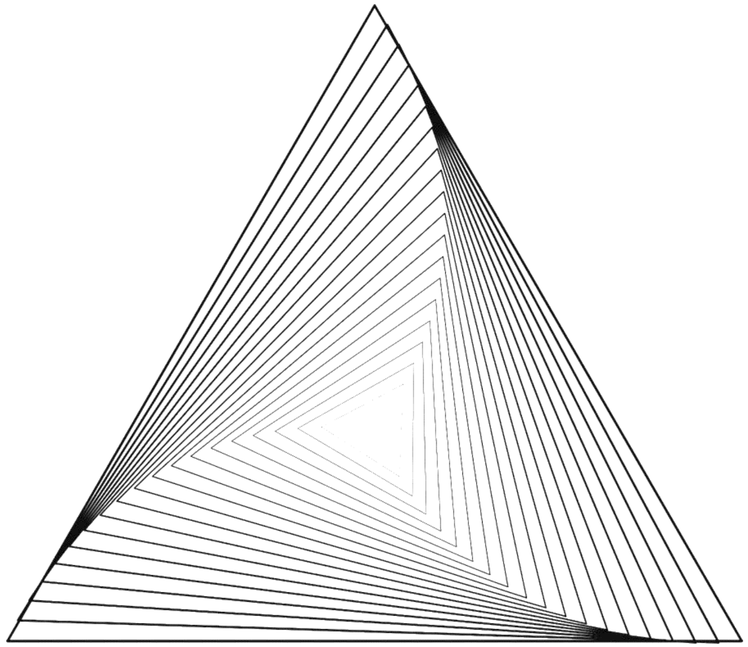
There are approximately 583,000 bridges in the U.S. ... are constructed ...oncrete, and the ... other construc- ...roximately 15% of ...ucturally deficient ...d steel and steel ...al direct cost estimates total $8.3 billion, including $3.8 billion to replace deficient bridges over the next 10 years, $2 billion for maintenance and capital costs for concrete bridge decks and $2 billion for their concrete substructures, and $0.5 billion for maintenance painting of steel bridges. Indirect costs to the user, such as traffic delays and lost productivity, were estimated to be as high as 10 times that of direct corrosion costs.

GAS AND LIQUID TRANSMISSION PIPELINES

Corrosion is the primary factor affecting the longevity and reliability of pipelines that transport crucial energy sources throughout the nation. There are more than 528,000 km (328,000 miles) of natural gas transmission and gathering pipelines, 119,000 km (74,000 miles) of crude transmission and gathering pipelines, and 132,000 km (82,000 miles) of hazardous liquid transmission pipelines. The average annual corrosion-related cost is esti-

Motivaciones y retos del SHM

- Improving safety.
- Automating inspections.
- Data for improving designs.



Motivaciones y retos del SHM

MAINTENANCE STRATEGIES

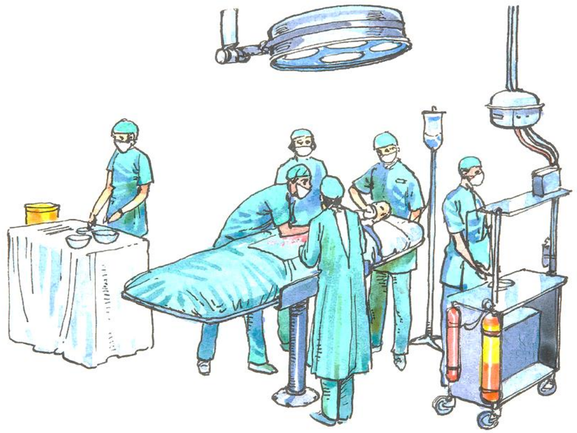
Ageing degradation

Motivaciones y retos del SHM

MAINTENANCE STRATEGIES

Ageing degradation

Corrective maintenance

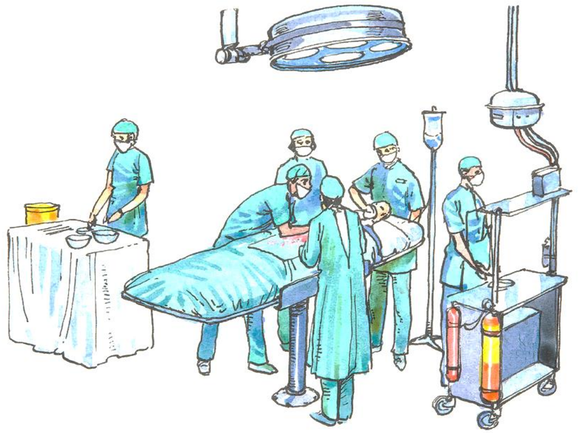


Motivaciones y retos del SHM

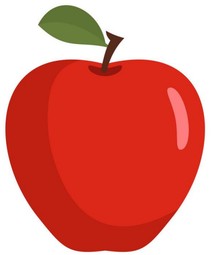
MAINTENANCE STRATEGIES

Ageing degradation

Corrective maintenance



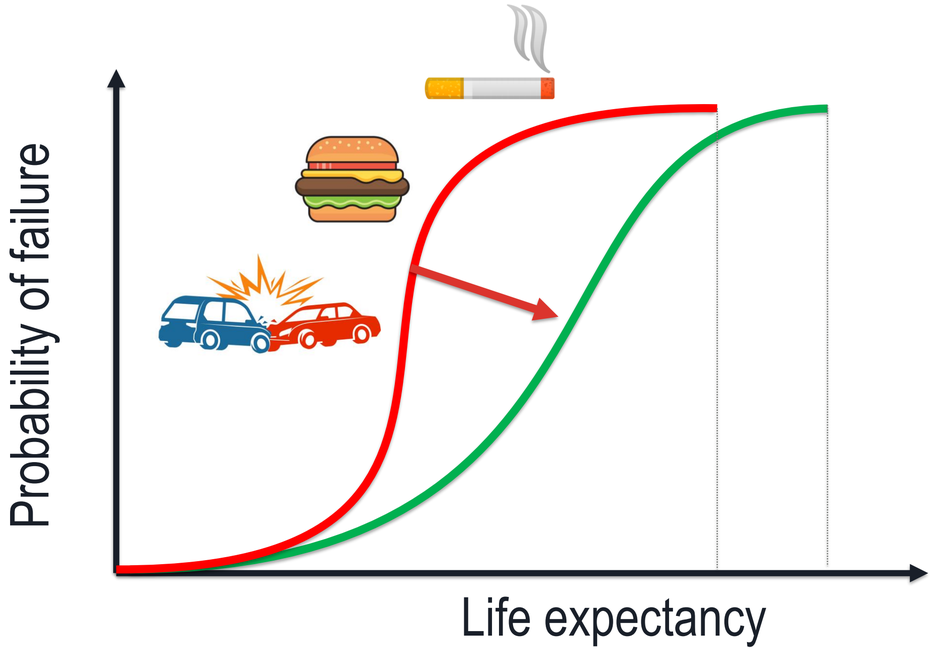
Preventive maintenance



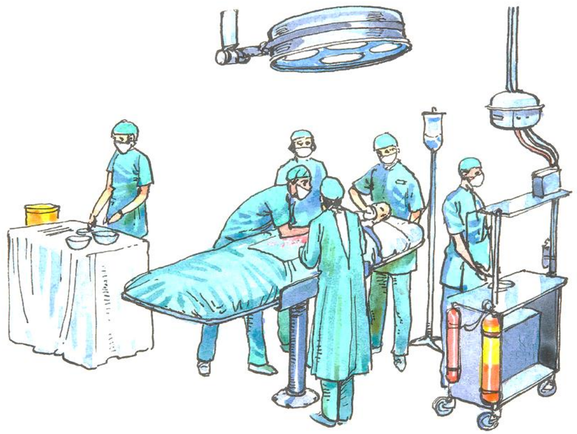
Motivaciones y retos del SHM

MAINTENANCE STRATEGIES

Ageing degradation



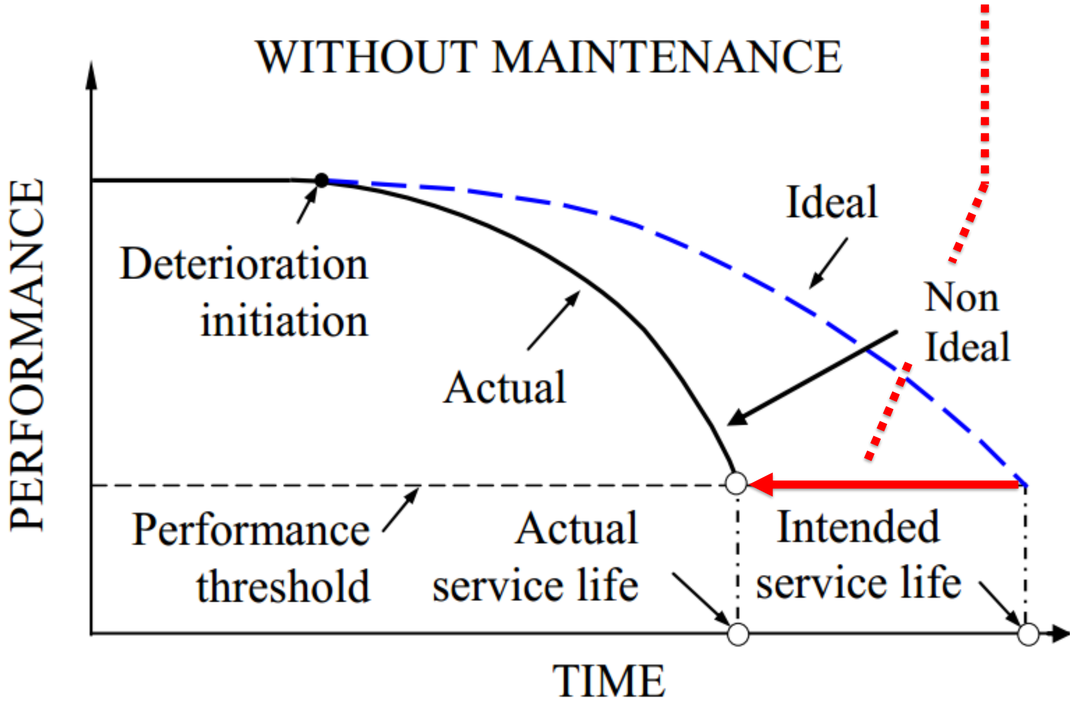
Corrective maintenance



Preventive maintenance

Motivaciones y retos del SHM

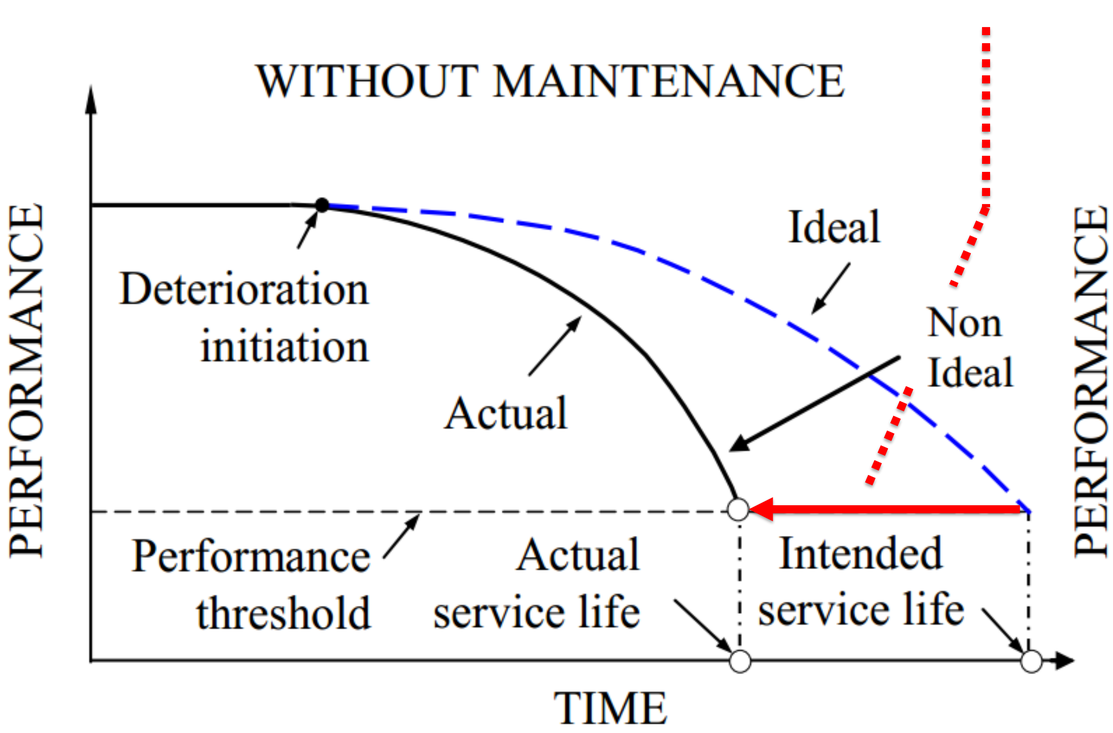
- Natural hazards
- Man-made disasters
- Accelerated aging



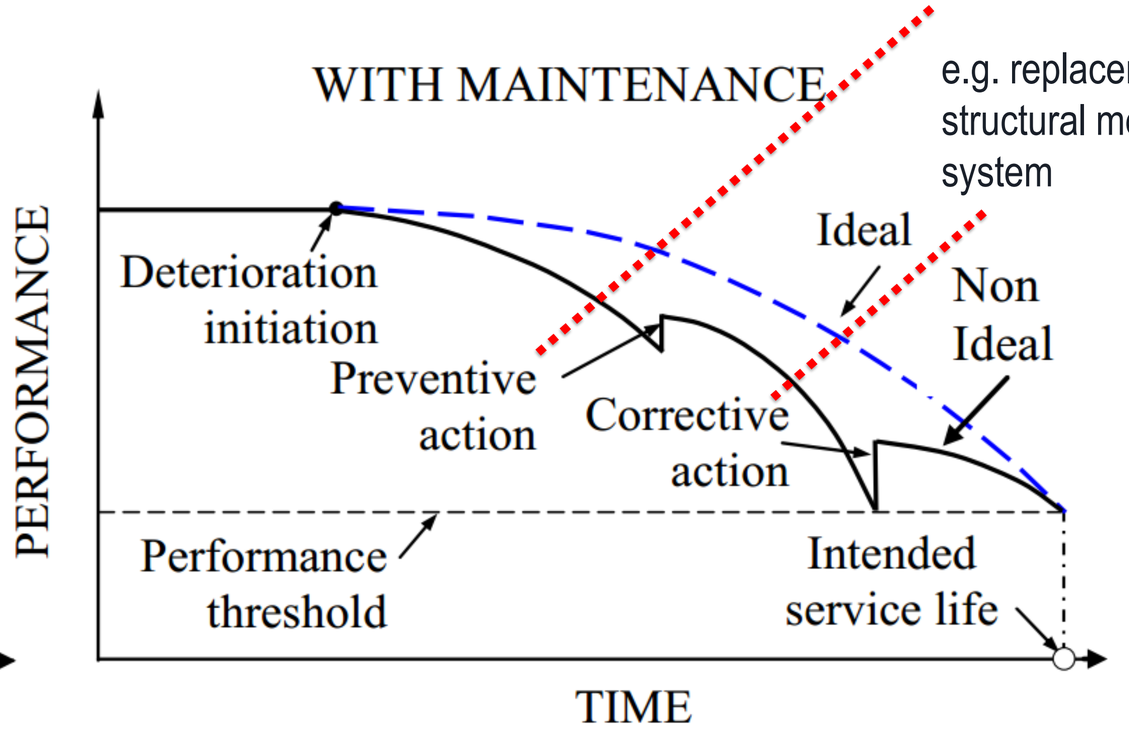
Motivaciones y retos del SHM

- Natural hazards
- Man-made disasters
- Accelerated aging

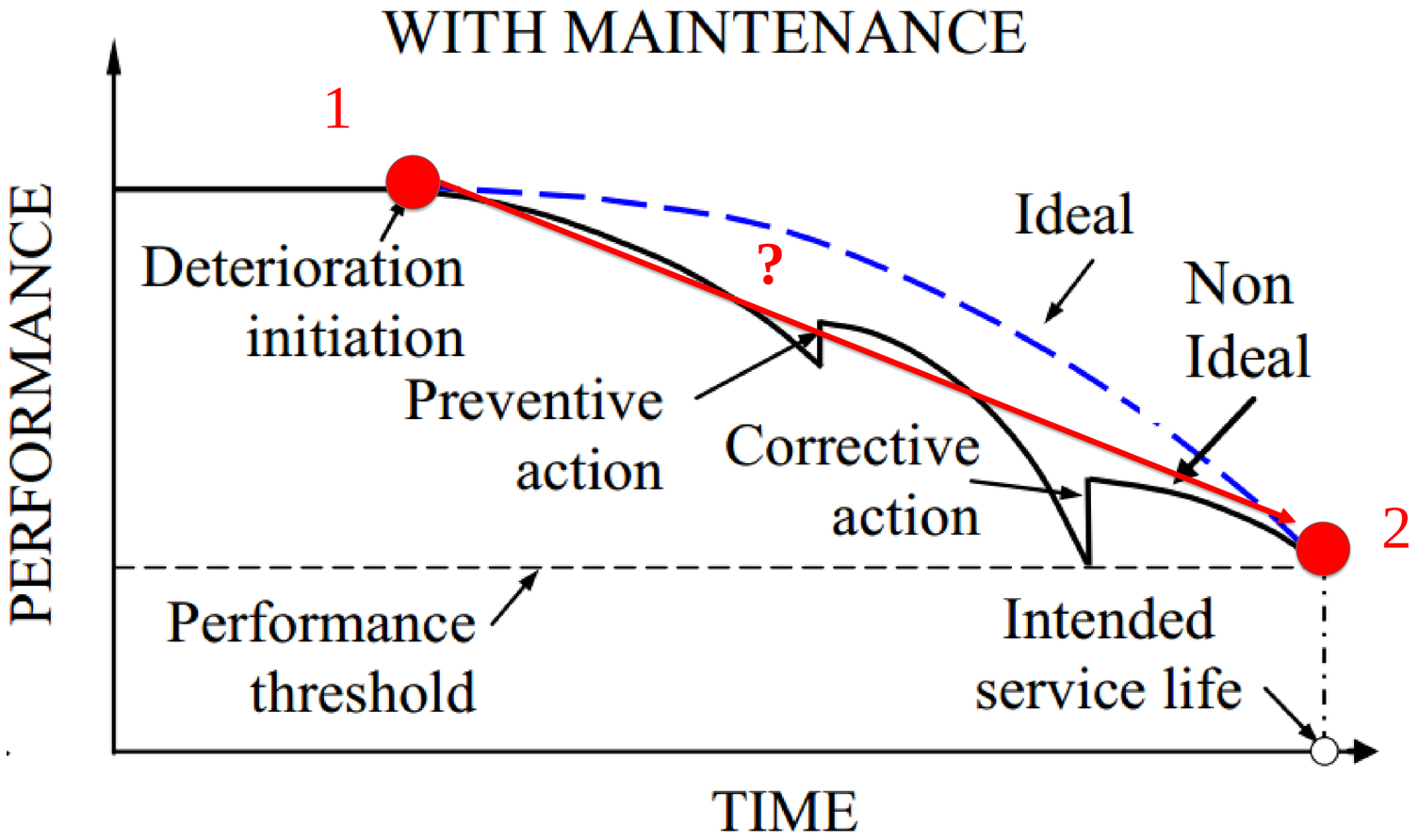
e.g. application of sealer on a bridge deck



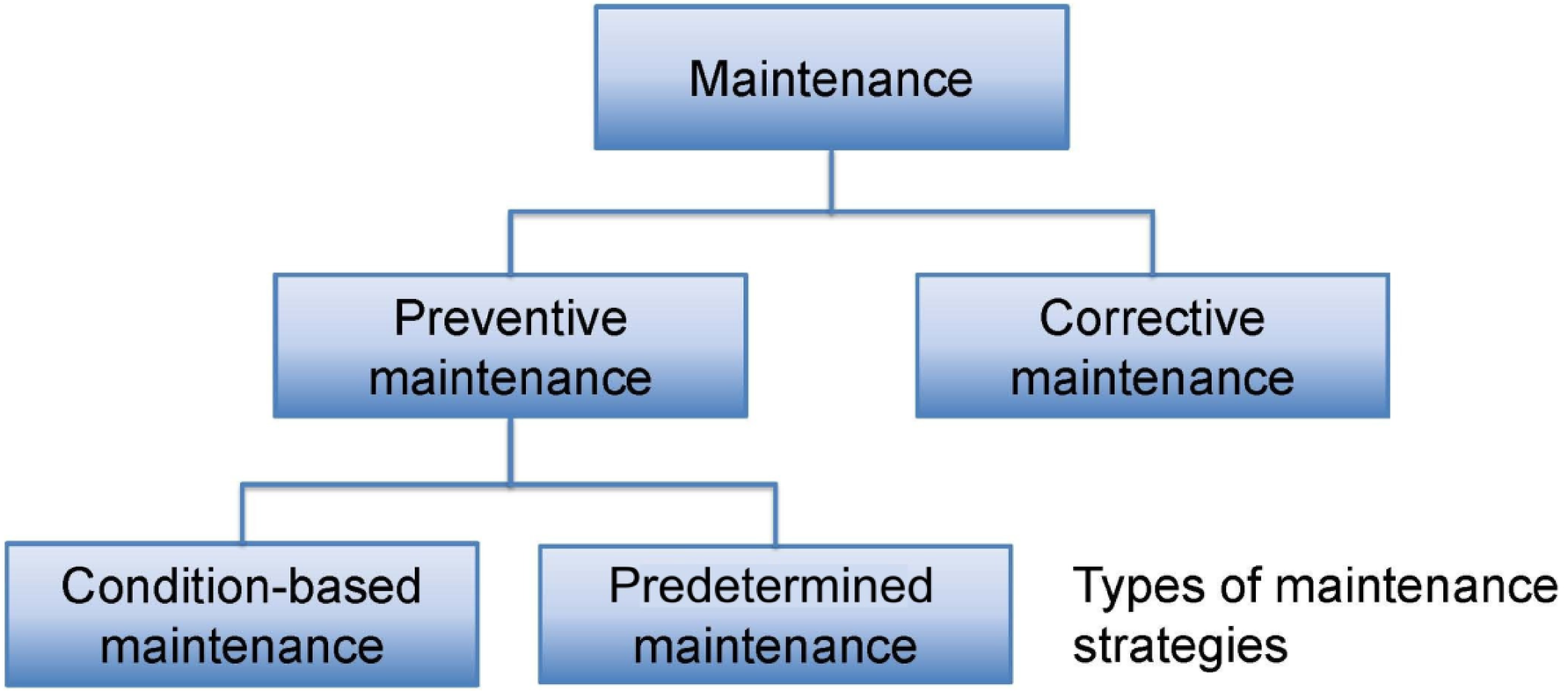
e.g. replacement of a structural member or system



Motivaciones y retos del SHM



Motivaciones y retos del SHM



Motivaciones y retos del SHM

Optimal intervals for time-based inspections?

Maintenance needs often are greater than available funds, decisions and scenarios for maintaining infrastructural systems must be based on a **life-cycle cost** (**LCC**) analysis.

(a) Reliable modeling of loadings (extreme loads, deterioration..etc)
(b) Prediction of structural safety and performance evolution.
(c) Estimation of costs of interventions.

Optimization problem

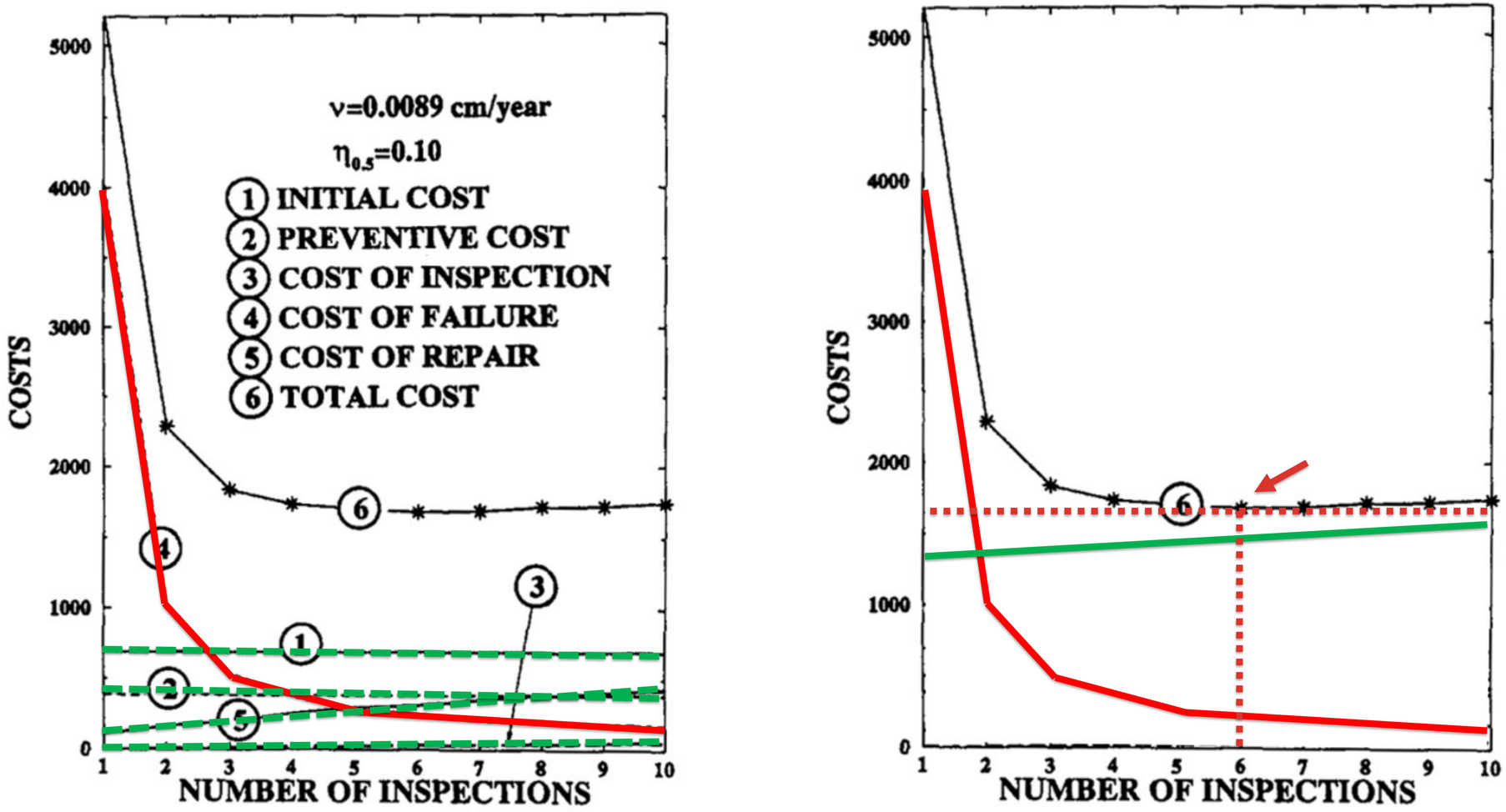
$$C_{ET} = C_T + C_{PM} + C_{INS} + C_{REP} + C_F$$

C_{ET}	Expected total cost
C_T	Initial design/construction cost
C_{PM}	Expected cost of routine maintenance
C_{INS}	Expected cost of performing inspections
C_{REP}	Expected cost of repairs
C_F	Expected cost of failure

Frangopol, D. M., Lin, K. Y., & Estes, A. C. (1997). Life-cycle cost design of deteriorating structures. Journal of structural engineering, 123(10), 1390-1401.

Frangopol, D. M., Dong, Y., & Sabatino, S. (2017). Bridge life-cycle performance and cost: analysis, prediction, optimisation and decision-making. *Structure and Infrastructure Engineering*, *13*(10), 1239-1257.

Motivaciones y retos del SHM

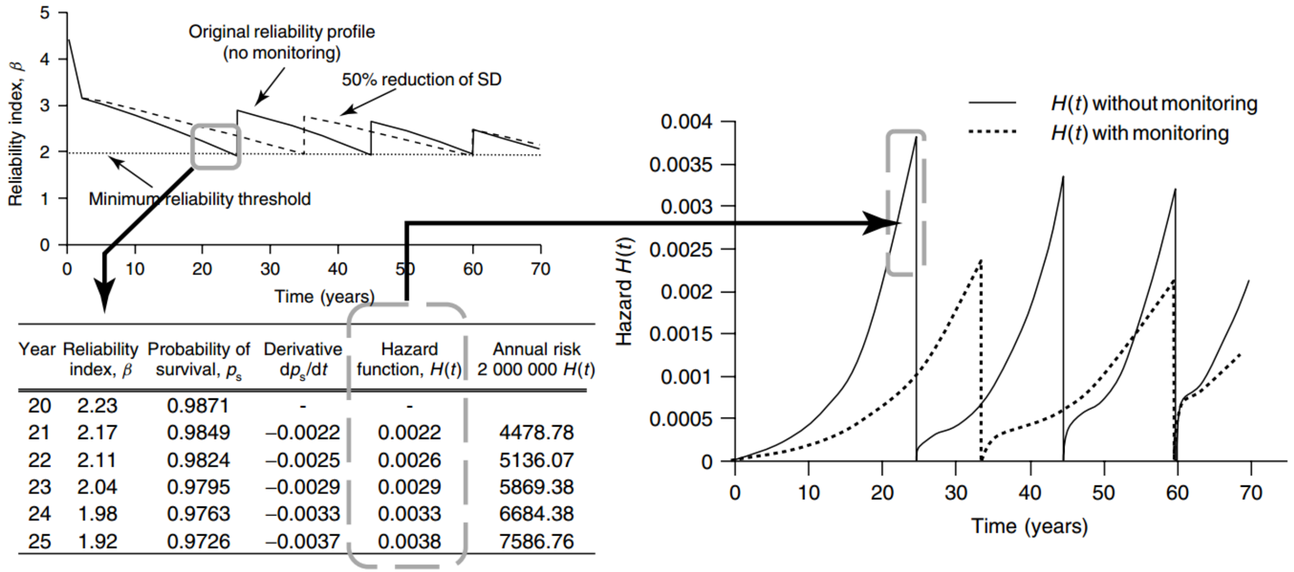


Frangopol, D. M., Lin, K. Y., & Estes, A. C. (1997). Life-cycle cost design of deteriorating structures. Journal of structural engineering, 123(10), 1390-1401.

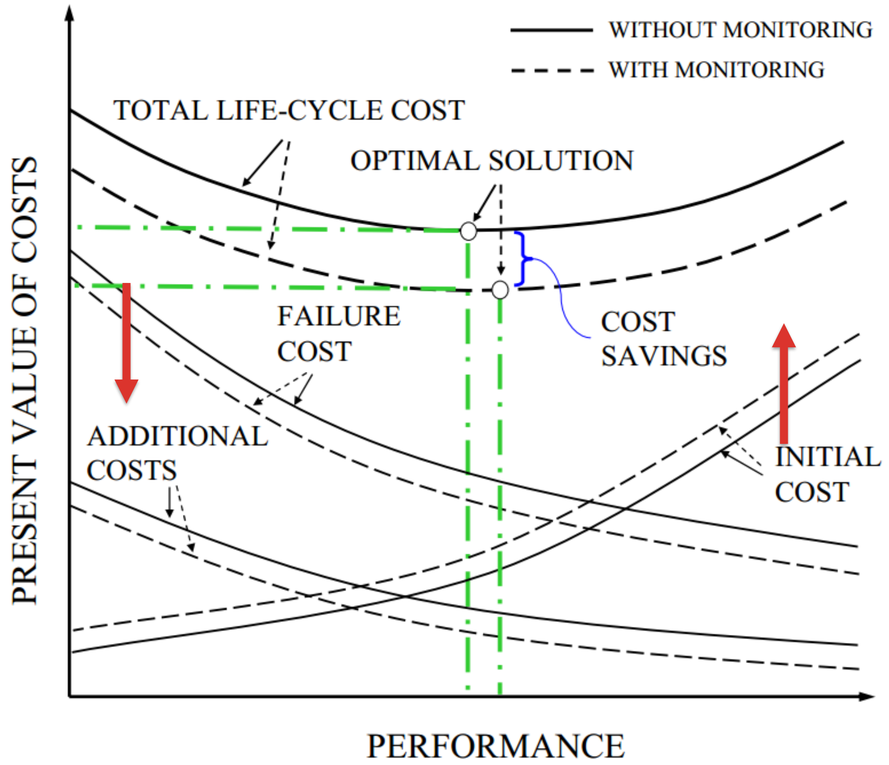
Motivaciones y retos del SHM

Automating inspections:
economic improvements for end-users

SHM → Hazard, n. of inspections



Year	Reliability index, β	Probability of survival, p_s	Derivative dp_s/dt	Hazard function, $H(t)$	Annual risk 2 000 000 $H(t)$
20	2.23	0.9871	-	-	
21	2.17	0.9849	–0.0022	0.0022	4478.78
22	2.11	0.9824	–0.0025	0.0026	5136.07
23	2.04	0.9795	–0.0029	0.0029	5869.38
24	1.98	0.9763	–0.0033	0.0033	6684.38
25	1.92	0.9726	–0.0037	0.0038	7586.76



Frangopol, D. M., & Messervey, T. B. (2009). Maintenance principles for civil structures. Encyclopedia of structural health monitoring.

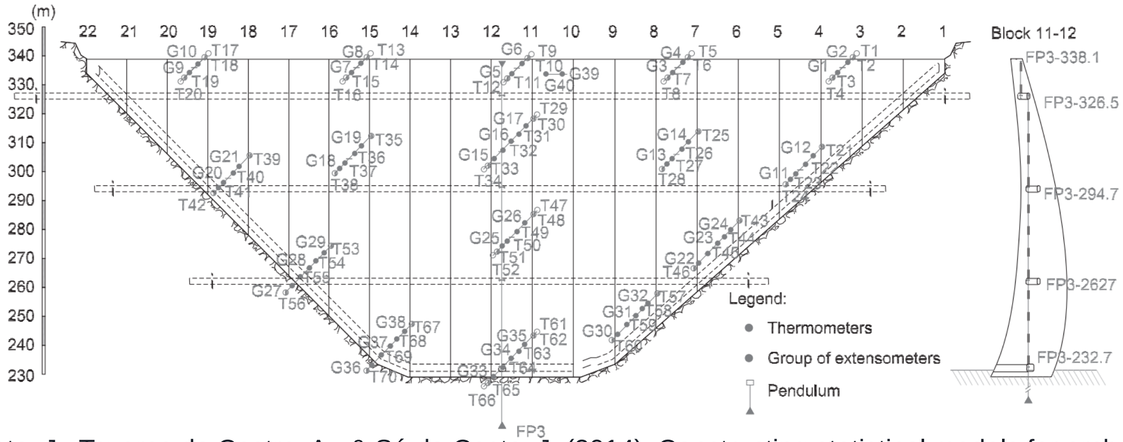
Faulstich, S., Hahn, B., Jung, H., Rafik, K., & und Prozessmodellierung, I. Z. (2009, January). Suitable failure statistics as a key for improving availability. In *Proceedings of the European Wind Energy Conference, EWEC*.

Motivaciones y retos del SHM

Saint Brieuc offshore wind farm

Motivaciones y retos del SHM

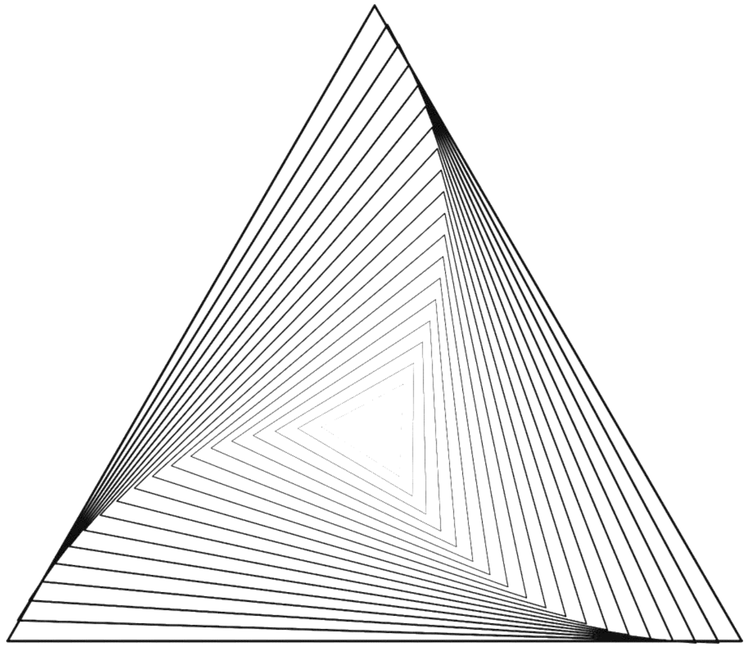
Alto Lindoso dam, Portugal



Mata, J., Tavares de Castro, A., & Sá da Costa, J. (2014). Constructing statistical models for arch dam deformation. *Structural Control and Health Monitoring*, *21*(3), 423-437.

Motivaciones y retos del SHM

- Improving safety.
- Automating inspections.
- Data for improving designs.



Motivaciones y retos del SHM

- ❖Improving safety.
- ❖Automating inspections.
- ❖Data for improving designs.

- Los datos de monitorización se pueden usar para confirmar o mejorar los coeficientes de seguridad de las acciones existentes, de resistencia y de las combinaciones de carga para eventos extremos usados en los códigos de diseño.
- La monitorización se puede utilizar para mejorar el diseño proporcionando al ingeniero la información estadística necesaria para emplear un diseño probabilístico basado en confiabilidad/desempeño/riesgo.

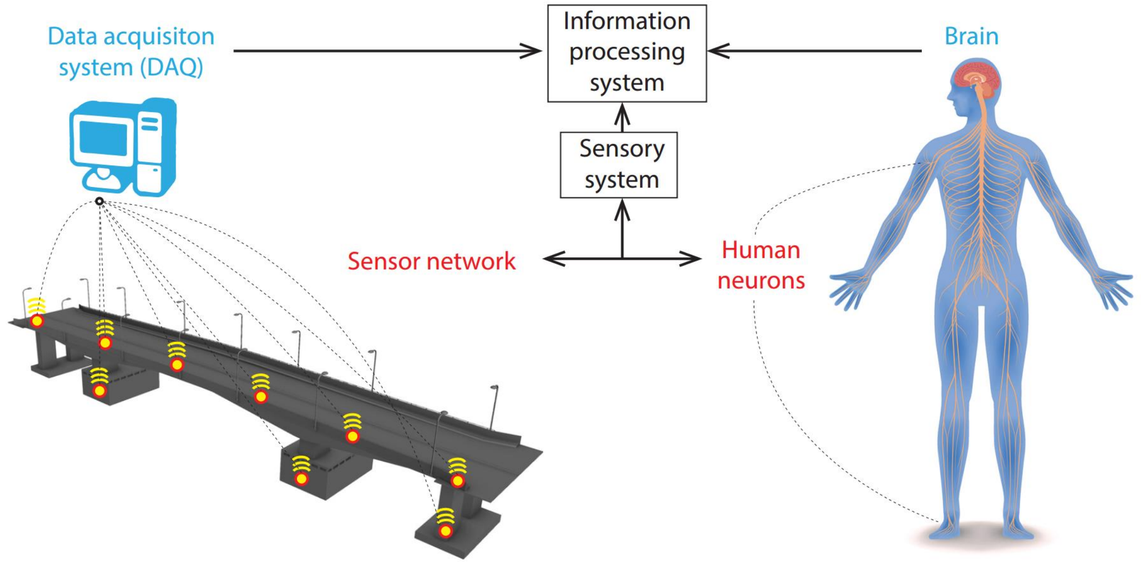
Motivaciones y retos del SHM

- Retos del SHM

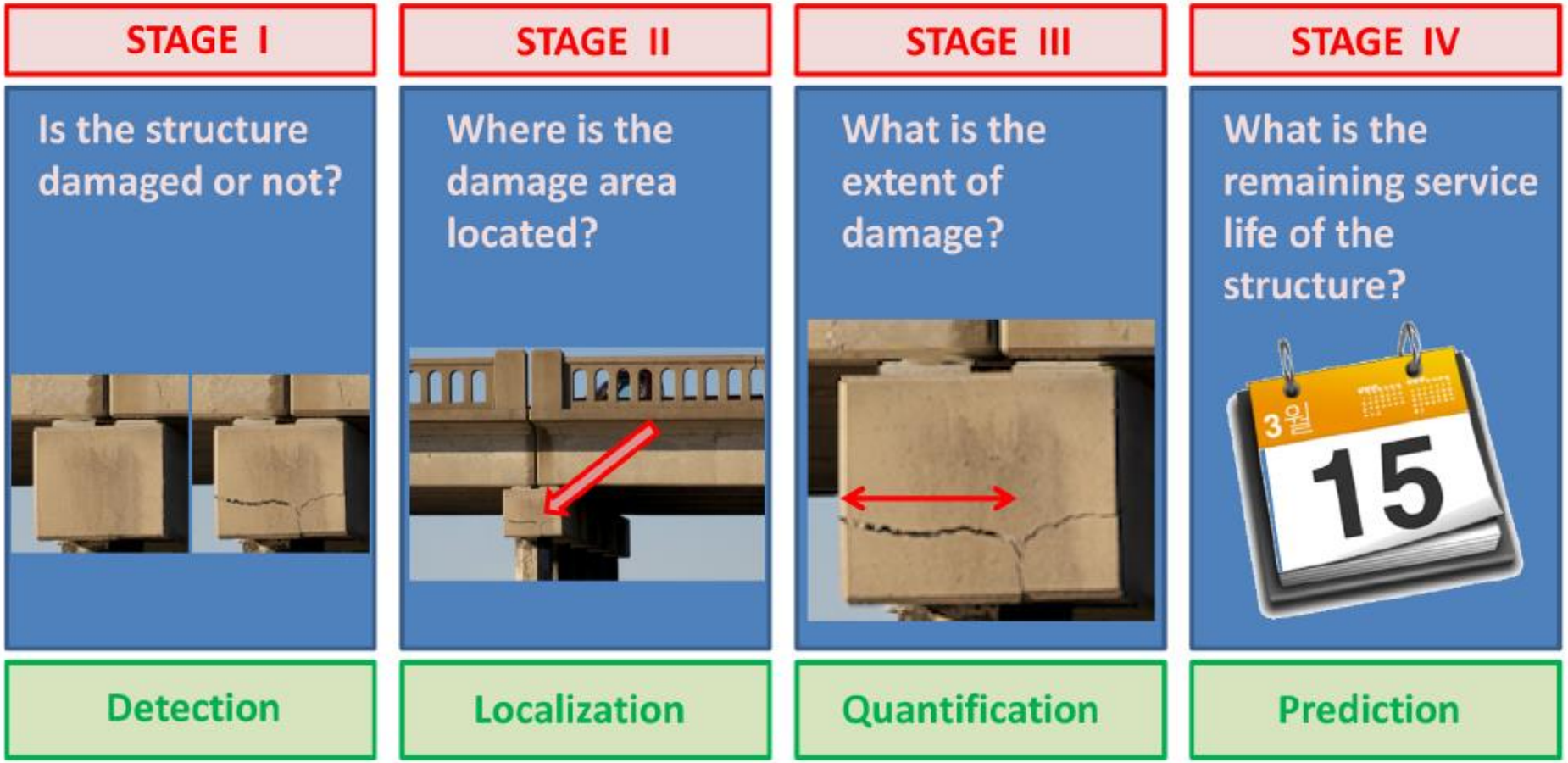
Motivaciones y retos del SHM

Structural Health Monitoring is highly Multidisciplinary!

- Sensors
- Data acquisition/transmission
- Sensor installation/application
- Data processing
- Structural/Material modelling
- Machine Learning
- Decision making
- ……



Motivaciones y retos del SHM



A. Rytter. Vibrational based inspection of civil engineering structures. PhD thesis, Aalborg University, 1993.

Motivaciones y retos del SHM

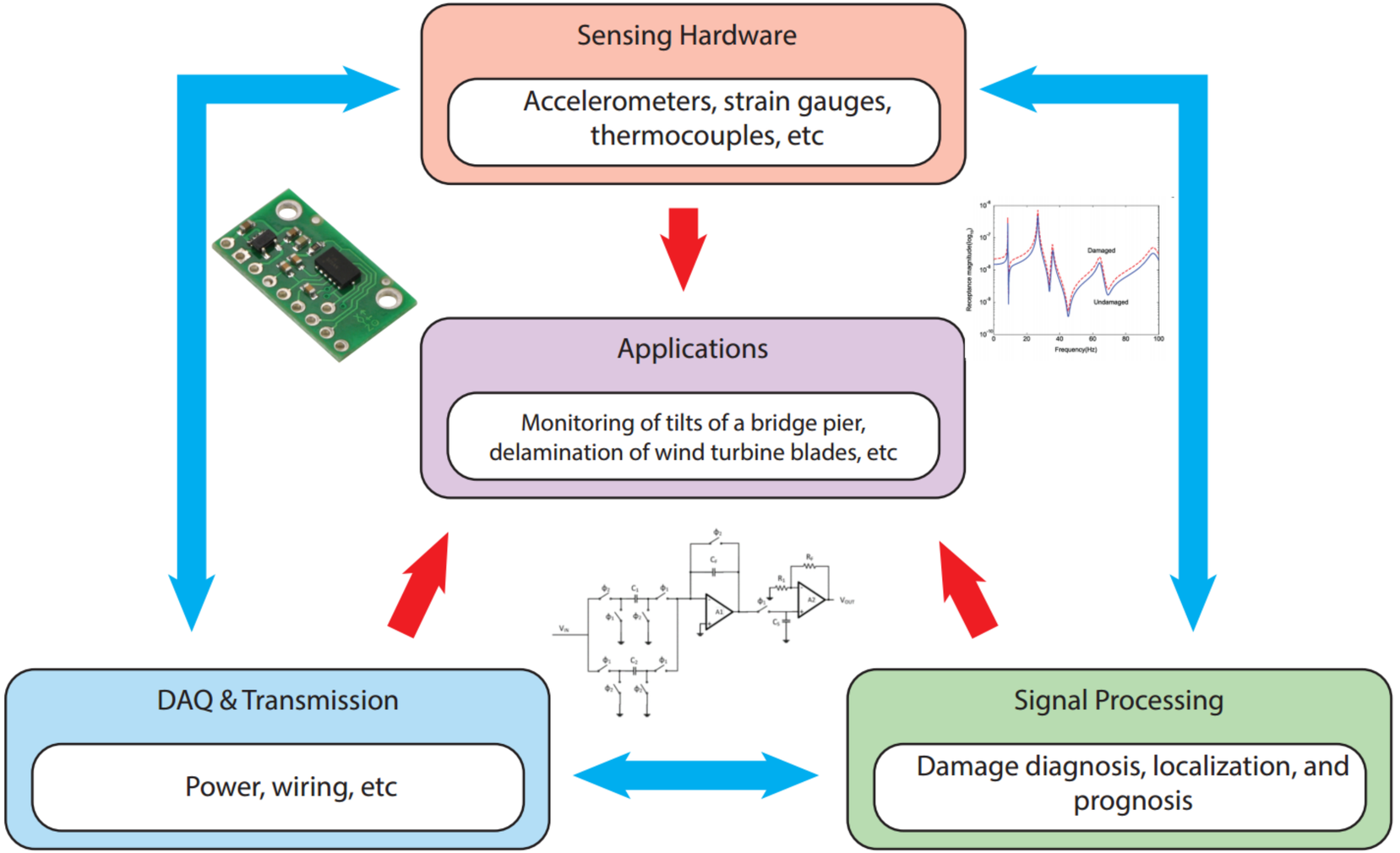
Ser capaz de diseñar soluciones SHM para sistemas a gran escala.

Específicamente, es necesario ampliar la comprensión de:

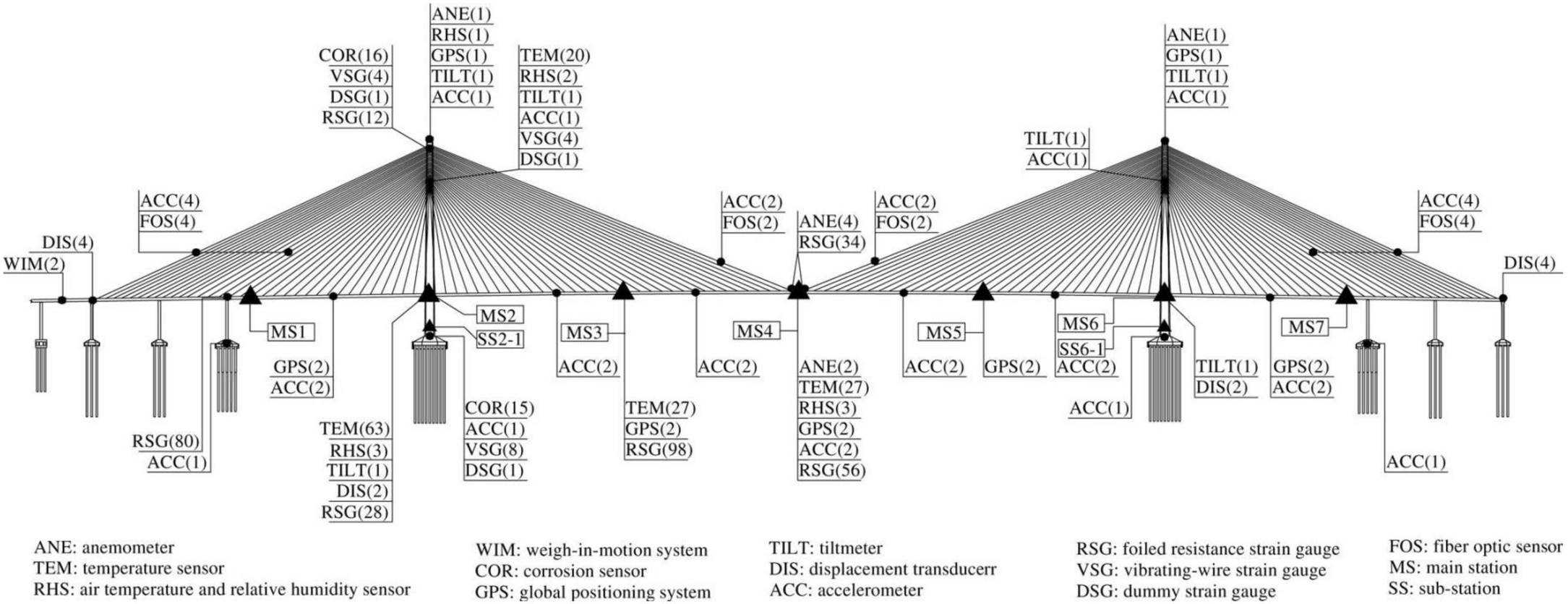
- Desafíos SHM para sistemas a gran escala (economía, aplicaciones, etc.).
- Transductores, adquisición de datos y técnicas de procesamiento de señales.
- Sistemas de decisión basados en mediciones.
- Aplicaciones en campo.

Motivaciones y retos del SHM

Sensor-based SHM



Motivaciones y retos del SHM



Mao, J. X., Wang, H., & Li, J. (2018). Fatigue reliability assessment of a long-span cable-stayed bridge based on one-year monitoring strain data. *Journal of Bridge Engineering*, *24*(1), 05018015.

Motivaciones y retos del SHM

Sensor-based versus application-based SHM

SHM Design

- ¿Qué quiero monitorizar?
- ¿Es útil la monitorización?
- ¿Cuánto retorno de la inversión obtendría?
- Identificar los estados que se deben monitorizar para una SHM exitosa

Structural Design

- ¿Qué quiero construir?
- ¿Es útil la estructura?
- ¿Cuánto retorno de la inversión obtendría?

- Diseño de hardware de detección
- Electrónica de diseño
- Diseñar algoritmos de procesamiento de señales

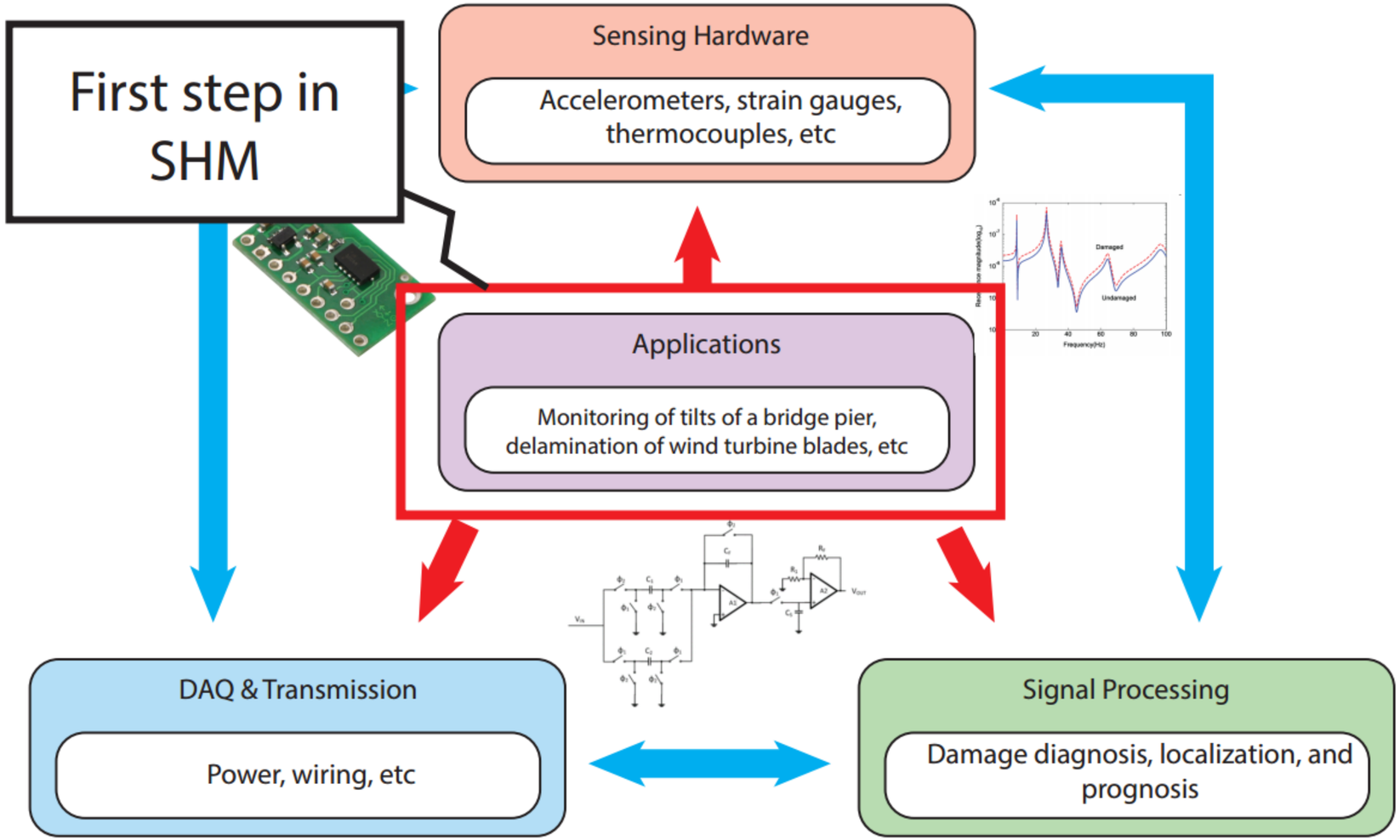
- Monitoriza la estructura

- Diseña la estructura

- Construye la estructura

Motivaciones y retos del SHM

Application-based SHM



Análisis modal como técnica revolucionaria

dentro del SHM.

Análisis Modal como técnica revolucionaria dentro del SHM

El análisis modal es una técnica más dentro del marco general del SHM!

Análisis modal como técnica revolucionaria dentro del SHM

$$M\ddot{u} + C\dot{u} + Ku = f$$

$$u(x,t) = q(t)\varphi(x)$$

Free vibration
Undamped system

$$(M\ddot{q} + Kq)\varphi = 0$$

Harmonic solution

$$q = A\sin(\omega t + \theta)$$

$$(-\omega^2 M + K)\varphi = 0$$ **Eigenvalue/Eigenvector problem**

Mode shapes/Natural modes of vibration

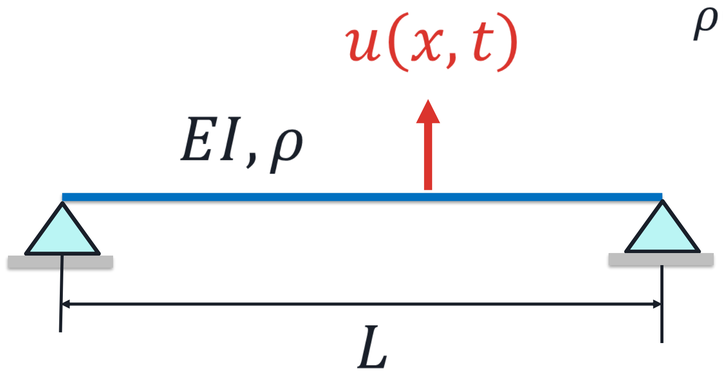
Natural frequencies/Resonant frequencies

El SHM basado en vibraciones, o pruebas dinámicas, se basa en la identificación de variaciones inducidas por daños en las propiedades modales de las estructuras (es decir, **frecuencias resonantes, formas modales y propiedades de amortiguamiento**).

- **Identificación global de daños**.
- Las patologías estructurales locales con efecto limitado sobre la rigidez general de las estructuras pueden pasar desapercibidas.
- El amortiguamiento (mecanismos de disipación de energía) es muy sensible al daño, sin embargo, su identificación depende en gran medida del nivel de excitación modal y generalmente está sujeto a altos niveles de incertidumbre.
- **La capacidad de un sistema SHM para detectar defectos localizados está directamente relacionada con su capacidad para identificar modos de vibración de alta frecuencia.**

- Hay dos tipologías principales de pruebas dinámicas:
- Utilización de excitaciones artificiales - **Análisis modal experimental (EMA)**.
- Uso de vibraciones ambientales - **Análisis modal operacional (OMA).**

Análisis modal como técnica revolucionaria dentro del SHM



$$\rho(x)\frac{\partial^2 u(x,t)}{\partial t^2} + \frac{\partial^2}{\partial x^2}\left[EI\frac{\partial^2 u(x,t)}{\partial x^2}\right] = 0$$

Variable separation

$$u(x,t) = \varphi(x)y(t)$$

Modal displacements

Mode shapes

+ BCs

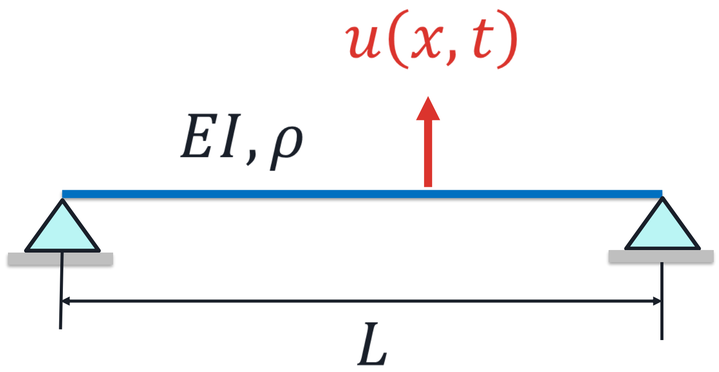
$$\varphi(x,n) = \sin\left(\frac{n\pi x}{L}\right)$$ Mode shapes

Orthogonality Property

$$\int_0^L \varphi(x)\varphi(x)dx = 0\ (i \neq j), 1\ (i = j)$$

$$\omega_n = n^2\pi^2\sqrt{\frac{EI}{\rho L^4}}$$ Natural angular frequency $$f_n = \frac{\omega_n}{2\pi}$$

Análisis modal como técnica revolucionaria dentro del SHM



$$\varphi(x,n) = \sin\left(\frac{n\pi x}{L}\right)$$

$$\omega_n = n^2\pi^2\sqrt{\frac{EI}{\rho L^4}}$$

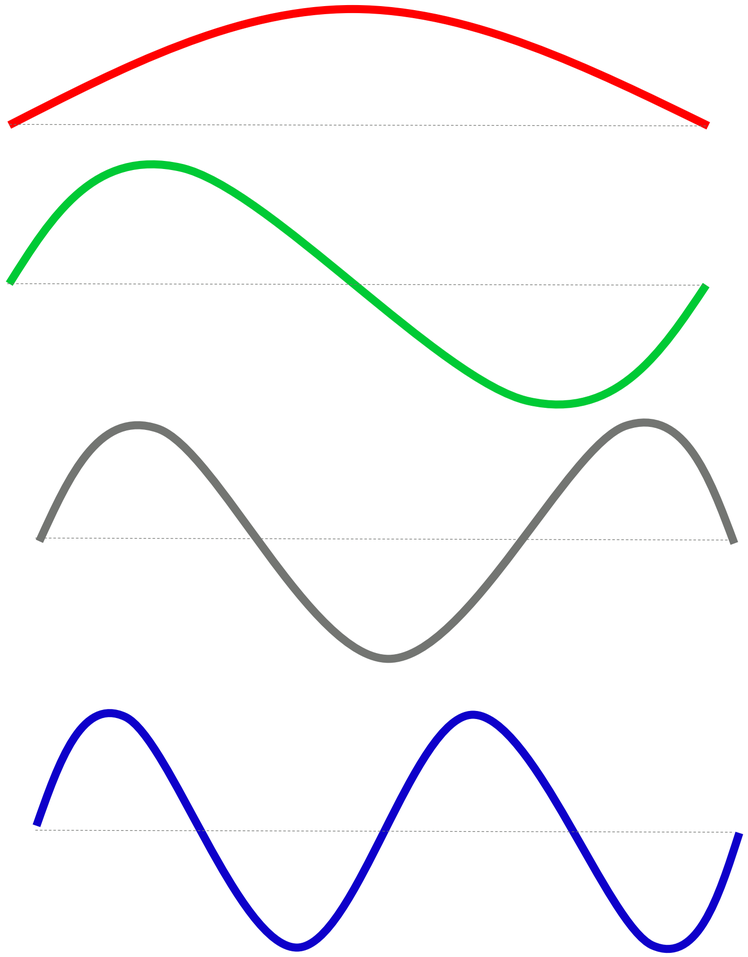
$$f_n = \frac{\omega_n}{2\pi}$$

Ejemplo: EI=7694081.0 kNm^2 , L = 15 m , ρ = 15000 kg/m^2

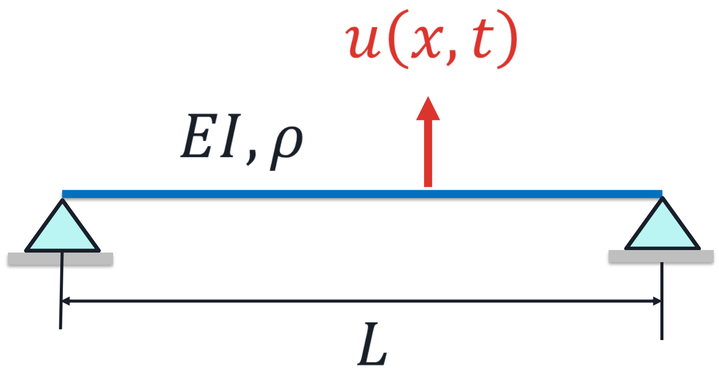
Mode 1 -> f=5 Hz

Mode 2 -> f=20 Hz

Mode 3 -> f=45 Hz



Análisis modal como técnica revolucionaria dentro del SHM



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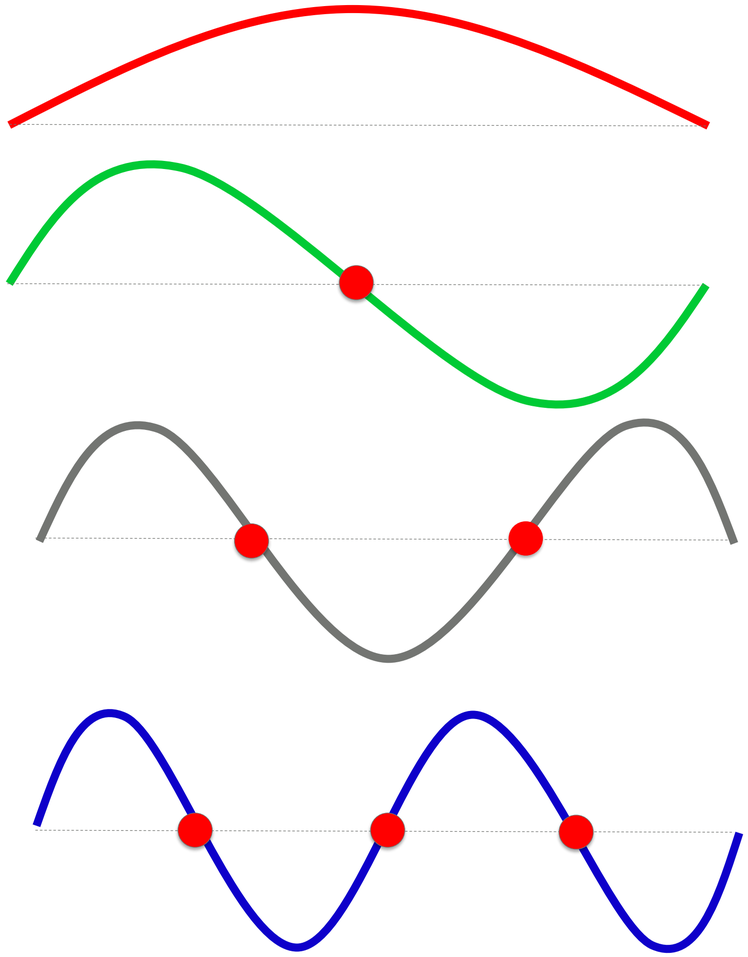
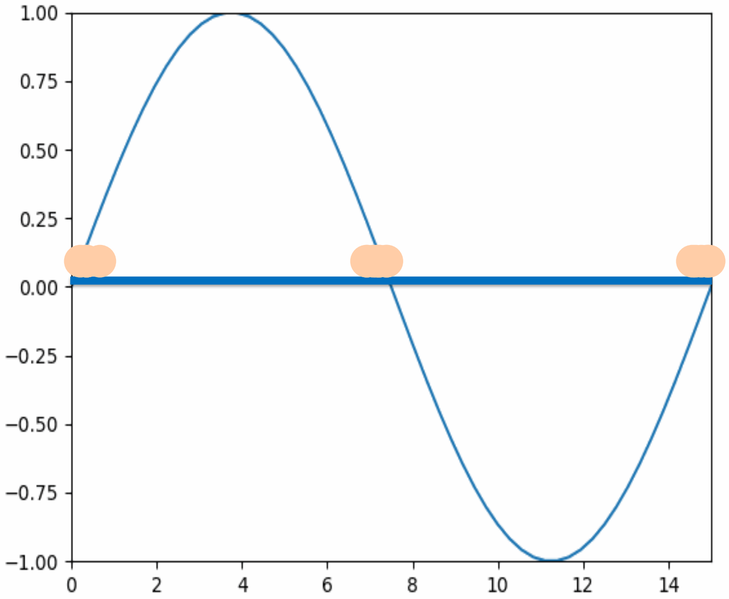
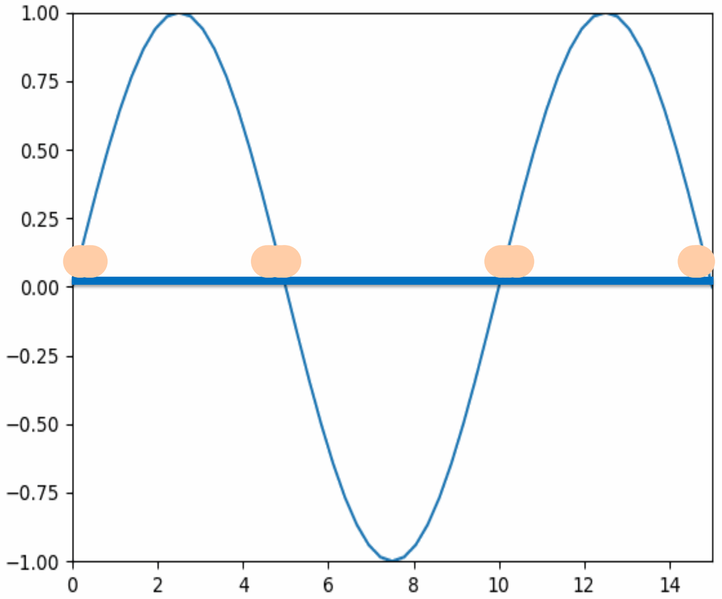
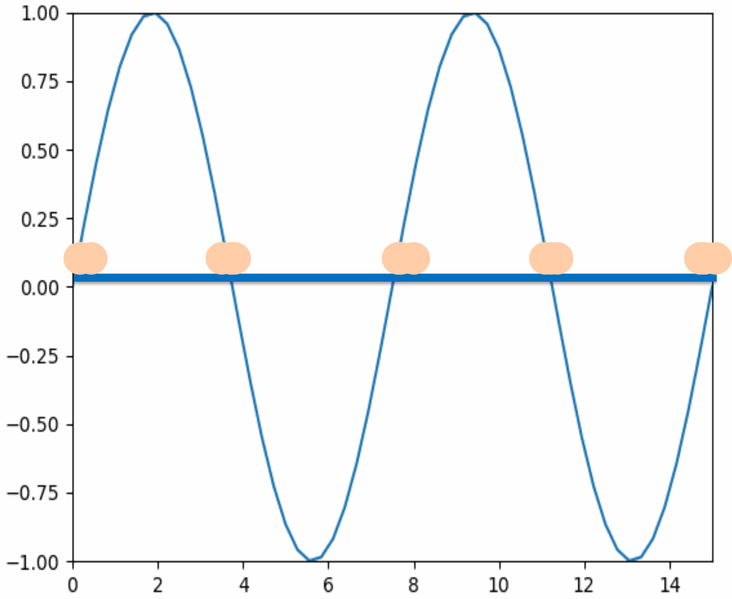


Análisis modal como técnica revolucionaria dentro del SHM

Análisis modal como técnica revolucionaria dentro del SHM







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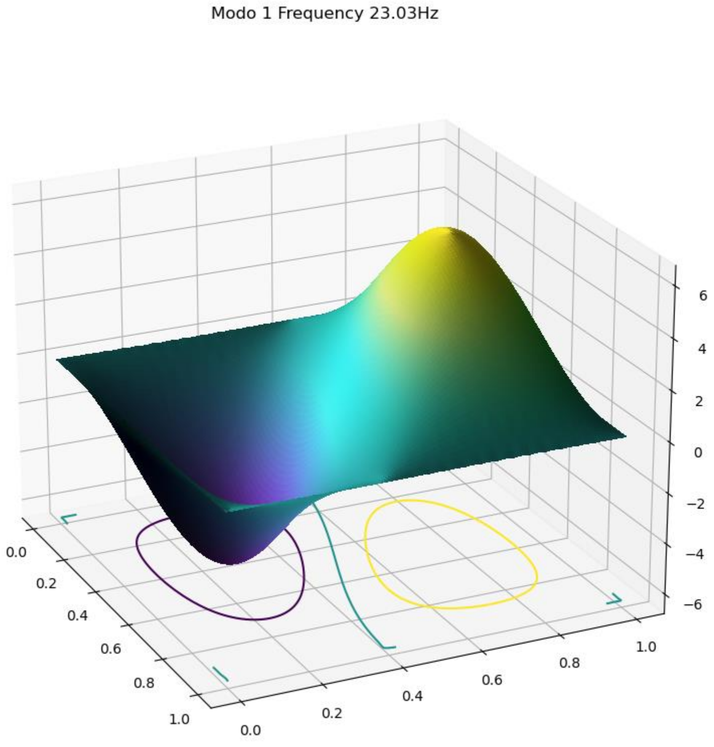

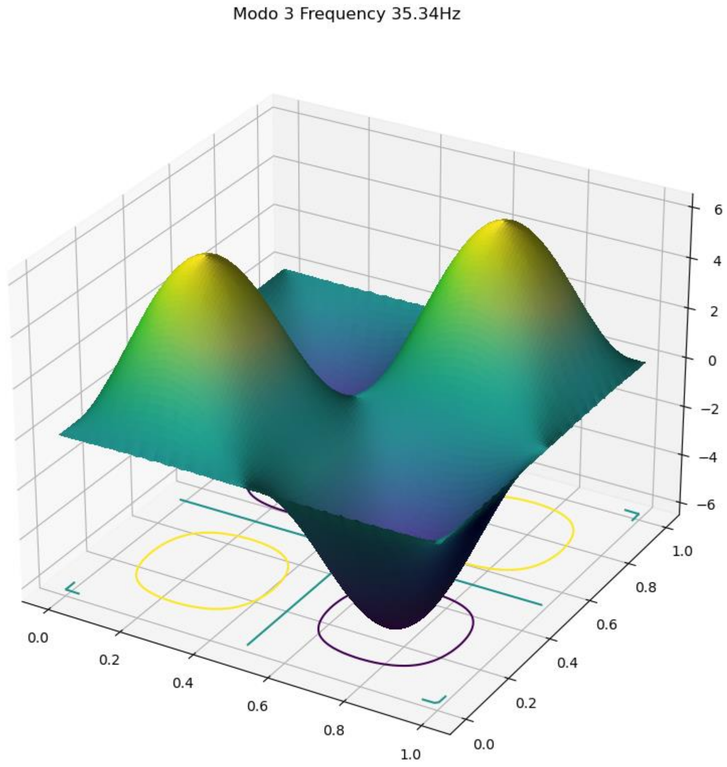

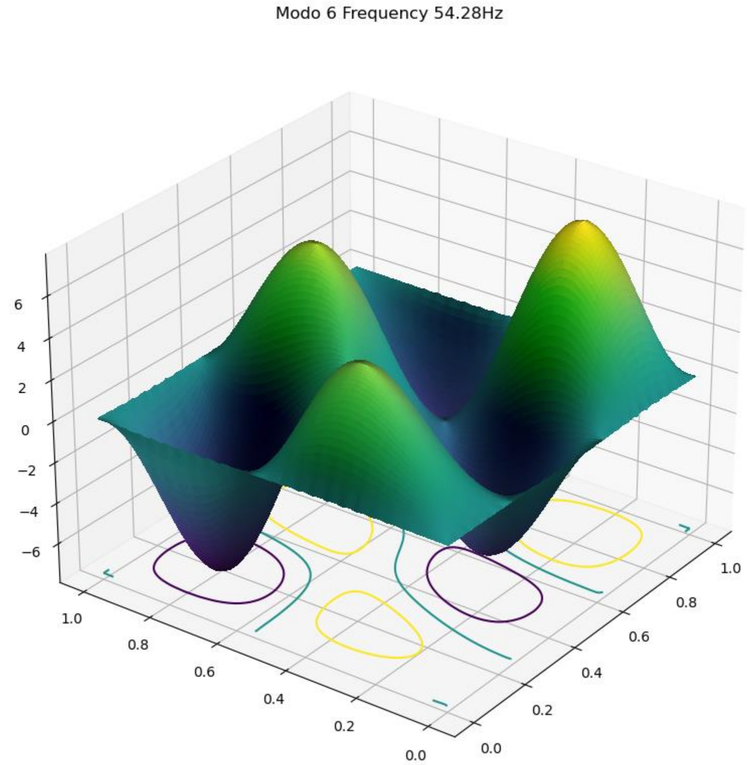

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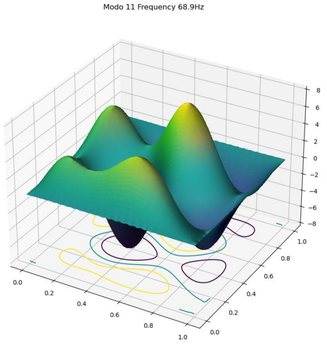

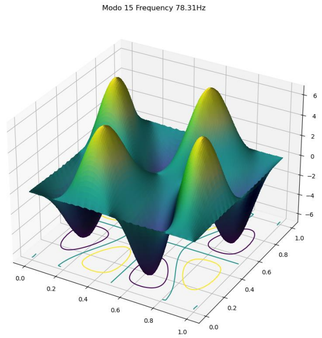

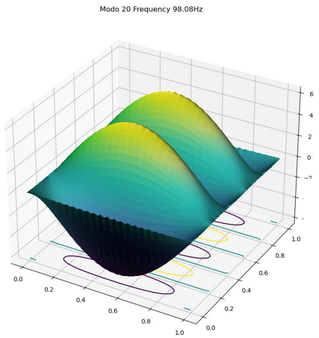

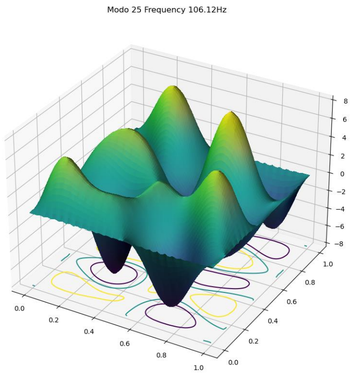

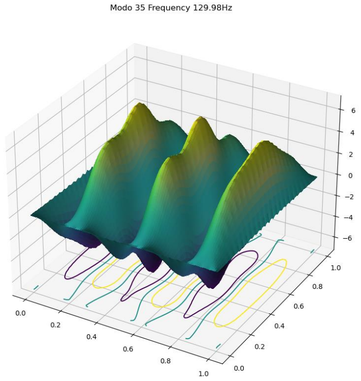

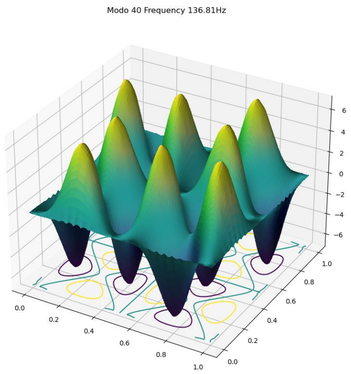

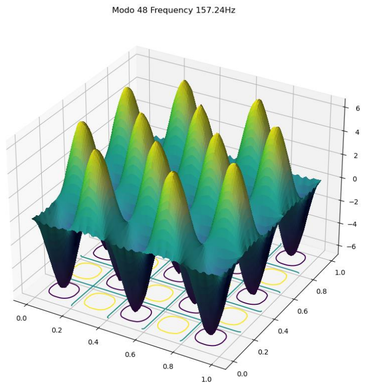

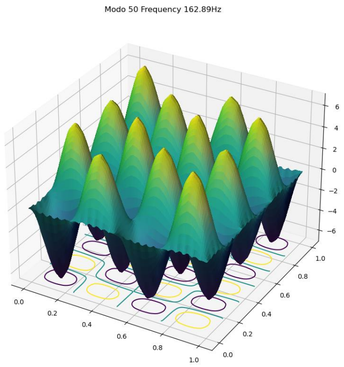

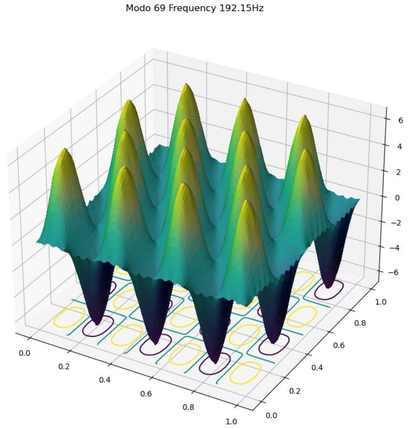

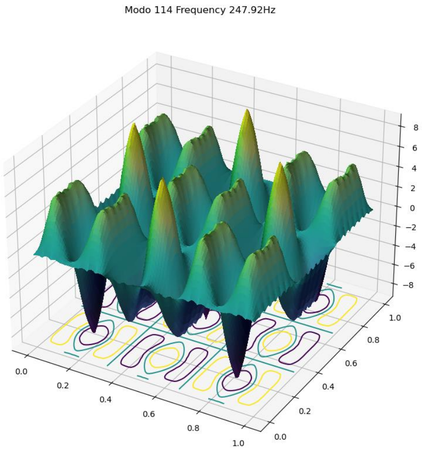

Frecuencia

Análisis modal como técnica revolucionaria dentro del SHM

https://www.youtube.com/watch?v=wvJAgrUBF4w

Análisis Modal como técnica revolucionaria dentro del SHM

Existen dos grandes variantes dentro del análisis modal:

- **Análisis Modal Experimental (EMA).** Las excitaciones de entrada son conocidas.
- **Análisis Modal Operational (OMA).** Las excitaciones de entrada son desconocidas.