Optimisation of structural health sensing system topology for maximising the value of information: An initial sketch of a theory

Piotr Omenzetter

Lloyd's Register Foundation Centre for Safety and Reliability Engineering, University of Aberdeen, UK

COST TU1402: Quantifying the Value of Structural Health Monitoring, Copenhagen, 24-25 August 2016

Motivation / Challenges

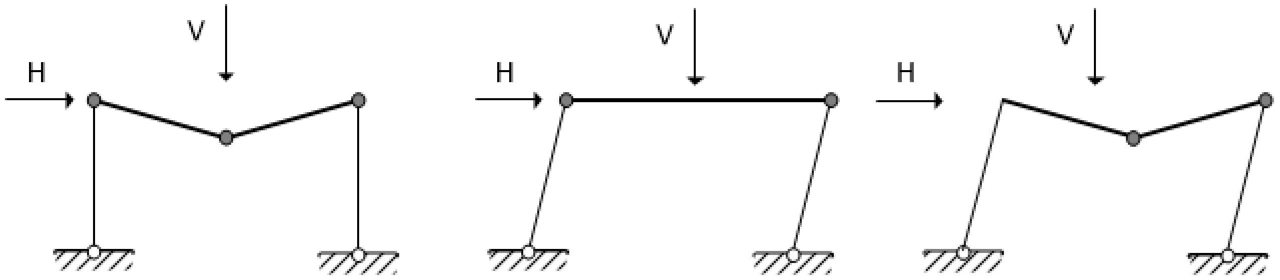
- Existing schemes for optimal sensor placement (sensing system topology) tend to focus on extracting ‘maximum amount of general information’ from measurements
- They do not consider how this information is intended to be used subsequently for specific applications (e.g. managing risk of structural failure) or the value of the information because they are not explicitly linked to failure probabilities and consequences

Objective

- To formulate an initial outline of a theory for optimal sensor placement for assessment of structural condition (or managing risk of structural failure) based on minimising the failure risk against the cost of data collection (maximising the value of information from monitoring)

Concepts from structural failure theory

- Reliability of a structural system is a function of reliability of its individual members
- Failure occurs when a mechanism is formed due to local failures of one or more structural members or cross-sections, e.g. buckling, plastic hinge, fatigue crack etc.
- There are typically several probable failure modes:



F_i = event 'occurrence of i-th failure mode'

f_j = event 'local failure of j-th member/cross section'

Linking failure theory with monitoring

- Probability of system failure:

$$P_f = P\left(\bigcup_{i=1}^{m} F_i\right)$$

m = number of failure modes

- Probability of i-th failure mode:

$$P(F_i) = P\left(\bigcap_{j=1}^{n} f_j\right)$$

Simultaneous failure of n members /cross-sections

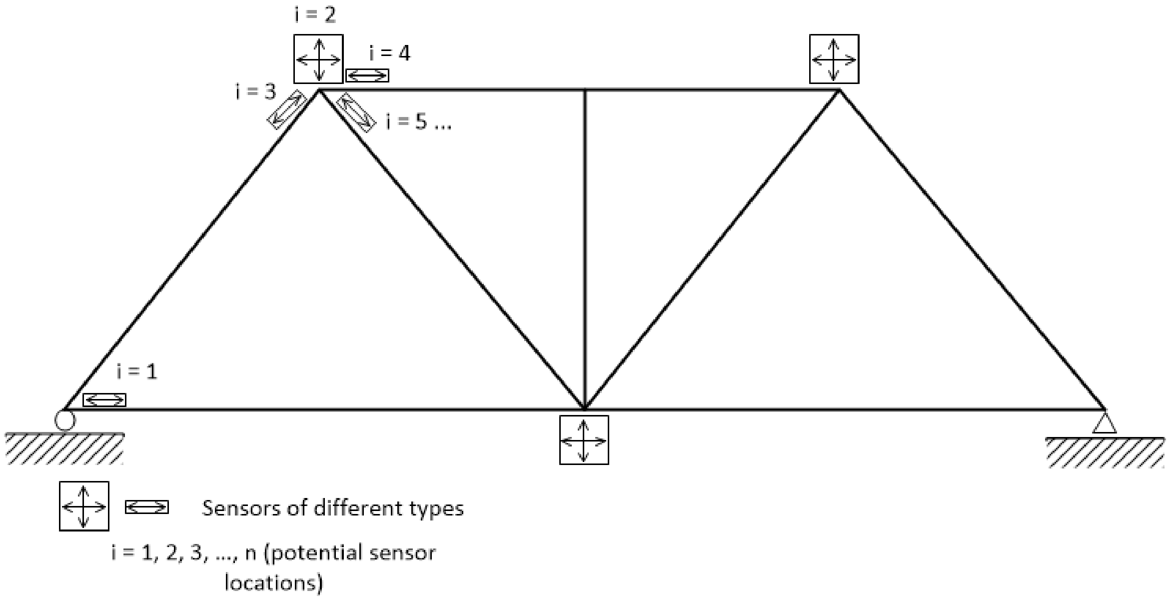
Data from monitoring systems can be used to update probabilities of local member/cross-section failures $P(f_j)$

Subsequently, these local failure probabilities can be used to update system failure mode probabilities $P(F_j)$ and then overall system failure probability

Consequences (costs) can be assigned to failures to calculate overall risk including cost of monitoring (pre-posterior analysis)

Risk can be minimised via optimal sensor placement (and/or optimal scheduling, monitoring system and data analysis ...)

Sensing system topology optimisation (1)



- Sensing system topology $\mathbf{p}_i = [1\ 0\ 1\ 0\ 0\ 0\ 1\ 1\ 0 \ldots]$
  1 = sensor present, 0 = sensor absent
- Monitoring data time series (strains, accelerations...)
  $\mathbf{m}(t) = [m_1(t)\ m_2(t)\ \ldots\ m_n(t)]$
- Feature extraction (max. strains, natural frequencies...)
  $\mathbf{r}_m(t) = f(\mathbf{m}(t))$

Sensing system topology optimisation (2)

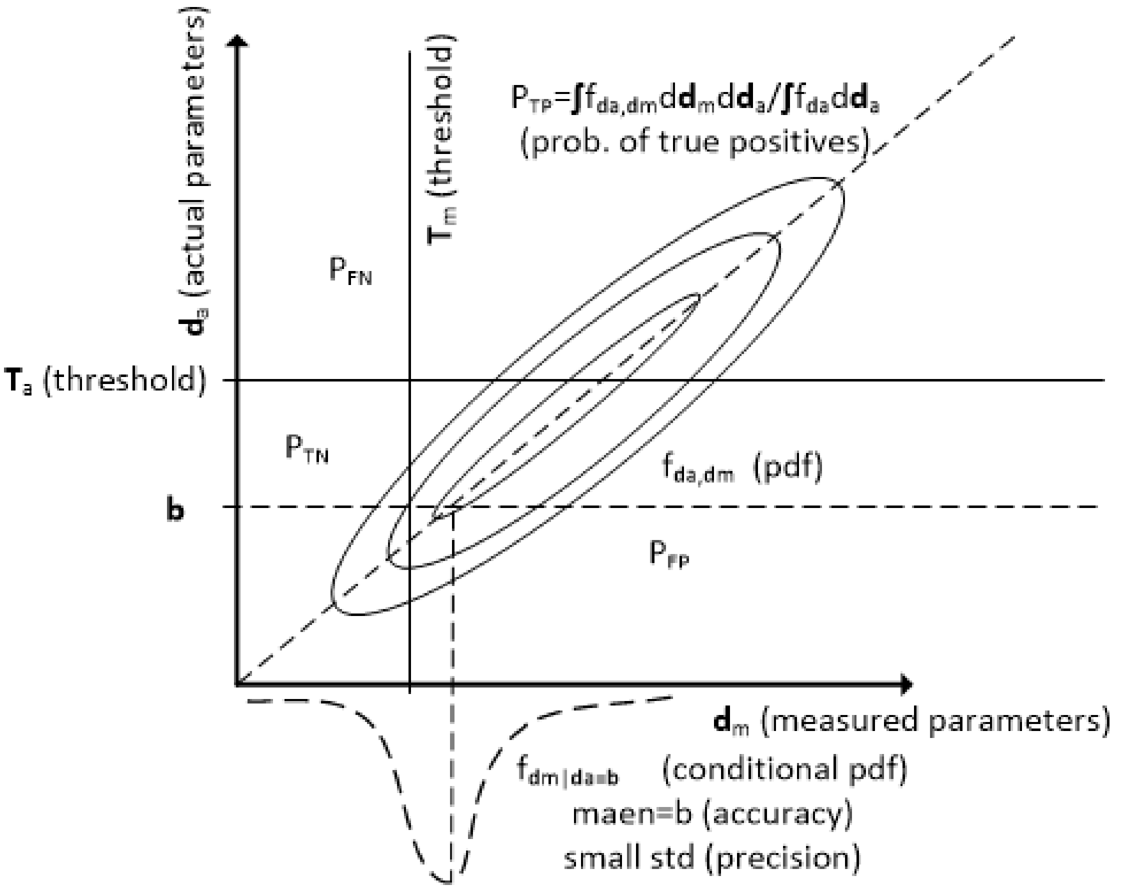
- Mapping of features into parameters that enable determination of reliability wrt. to failure modes (strains, stresses and their resultants...)

$$\mathbf{d}_m(t) = g(\mathbf{r}_m(t)) = g(f(\mathbf{m}(t)))$$

- Critical but challenging, and currently underdeveloped, link
- Need for damage localisation and severity assessment (if damage detection method is to be more than just a precursor for further investigations)

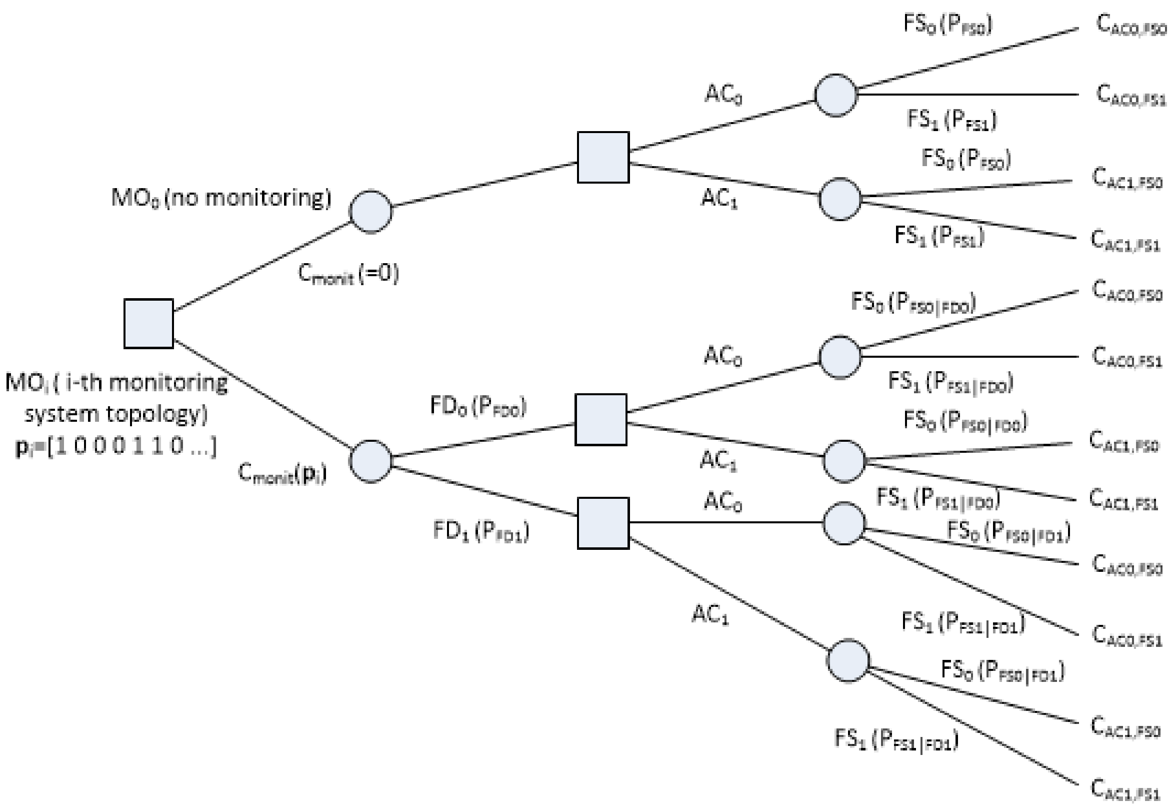
Sensing system topology optimisation (3)

- Modelling of damage detection method performance for individual members/cross-sections to find $P(f_j)$s



Sensing system topology optimisation (4)

- Pre-posterior analysis for optimal sensing topology determination



AC = actions resulting from failure detection (e.g. vehicle load restriction or bridge closure)

$\mathbf{C_{AC,FS}}$ = consequences/costs of actions depending on actual state of nature (failure occurrence)

$$MO_{opt} = \min_{MO_i \in \mathbf{MO}} E_{FD} \min_{AC_k \in \mathbf{AC}} E_{FS|FD} \left[C\left(MO_i, FD_j, AC_k, FS_l \right) \right]$$

Concluding remarks

- A theory for optimising sensing system topologies for maximising the value of information has been outlined for assessment of structural condition (or managing risk of structural failure) based on minimising the failure risk against the cost of data collection
- The basic premise is to use measurements to create features that map into parameters that relate to local member/cross section failures (e.g. formation of plastic hinges)
- These parameters from measurements may be used to update local member/cross section failure probabilities, system failure mode probabilities and total system probabilities.
- Assigning consequences/costs to failures and using pre-posterior analysis enables to calculate the risk reductions associated with each candidate sensing system topology and choosing the topology that is optimal in this sense.
- Challenges for applications to real, complex structural systems include:
  - Determination of all relevant failure mechanisms and associated probabilities
  - Constructing features from measured signals that correlate well with reaching maximum capacity in critical members/cross sections
  - Efficient computational algorithms for solving the optimisation problem (engineering judgment to determine hot spots should be utilised)

Acknowledgement

Piotr Omenzetter’s work within the Lloyd’s Register Foundation Centre for Safety and Reliability Engineering at the University of Aberdeen is supported by Lloyd’s Register Foundation. The Foundation helps to protect life and property by supporting engineering-related education, public engagement and the application of research.

EURODYN 2017

MS14 - Structural Health Monitoring

Co-chaired by Alvaro Cunha & Piotr Omenzetter

Abstracts due September 12th