Sensor Placement to Monitor Launching Girder Operations in Segmental Construction

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ABSTRACT

The paper aims at providing a methodology for designing a system for monitoring launching girder operations on precast segmental construction projects. An optimal sensor placement strategy is developed to identify the current state of the launching girder with the minimum number of sensors. A class of structural models was created by varying the initial conditions and then analysed using a finite element analysis package to get responses at different locations. Entropy at these locations were calculated and the locations with the highest entropy is chosen as an optimal sensor location. Influence of precision of sensors in design of measurement system is also discussed in detail. Increase in precision results in increased information content and lesser number of sensors.

Keywords – Sensor placement, Launching girder, Shannon's entropy, Information theory, Automated construction monitoring, Measurement system design

1 Introduction

Launching Girder is an equipment extensively used in the prefabricated segmental construction of viaducts. It is used to lift, assemble, post-tension and load the spans of bridges constructed using the incremental launching method. Although automation of launching girder has many advantages such as improved construction efficiency, reduction in accidents, smooth operation, etc., currently, there is limited automation in the operation of launching girders worldwide. In order to automate the construction process, real time data pertaining to the state of the launching girder such as the current launch position, pressure in hydraulic pumps, internal forces, etc. are required. In addition, it is essential to ensure that assumptions made during the design phase are valid during the operation phase. Even though conservative assumptions are usually made, the impact of these assumptions is rarely studied. A sensing system capable of measuring structural responses of the launching girder aids in determining the state of the launching girder during the construction phase. It also helps to validate the assumptions made during the design phase.

The sensing system should be free of human interventions due to the high cost, human errors associated with it and the response time. An automated sensing system using wireless sensors is ideal for the requirement. Wired network may not be practical for the current requirement, as the interference from construction operations would introduce a high risk of system failure [1]. Though wireless sensor network seems to be an ideal solution, there are challenges in designing a wireless sensor network for outdoor applications, which include reliable communication and power requirements. Fundamental risk in implementing a wireless sensor network in a construction site is that radio frequency environment is characterized by limited coverage, interference from electromagnetic fields generated by operating engines, multipath signal fading and non-line of sight conditions, which severely affect wireless signal propagation [2]. On top of these technological challenges, there are computational challenges in determining the optimal sensor configuration. Determining the sensor locations, which contribute to maximum information content, is a combinatorial optimization problem reported to be NP-Complete [3].

The optimal sensor placement strategy aims to identify the current state of the launching girder with the minimum number of sensors. It should be able to distinguish between the many potential scenarios that are possible during the operation. Uncertainties in environmental conditions, quality of work, human errors as well as the actual activities performed create many scenarios, which have to be correctly identified and evaluated for safety and other aspects. Correct identification of the state will also help to verify design assumptions and evaluate the potential for optimization.

A methodology based on Shannon's entropy [4] is proposed in this paper to ensure optimal placement of sensors. Details of the sensor placement strategy are discussed in detail. The methodology will be validated using data from the implementation on a full-scale segmental construction scenario and design assumptions will be verified.

This paper aims at providing a methodology for optimal sensor placement in a launching girder in order to identify different operations of the launching girder. Brief outline of the research in the past is given in section 2. Section 3 conveys the methodology used for the strategic sensor placement and section 4 discusses the implementation of the methodology in a launching girder. Results of the sensor placement is discussed in section 5 and section 6 contains conclusions. Review of Past Work

2 Review of Past Work

It can be seen that the trend in monitoring of civil engineering structures for early anomaly detection through measurements using large number of sensors is increasing. However, methodology followed in arriving at a sensor configuration is not systematic. The number of sensors to be used and their locations are decided based on engineering judgment. This may result in instrumentation with many sensors, which would lead to large amount of redundant data. This increases the cost of interpretation and might result in insufficient data leading to ambiguous interpretation [5]. Therefore, a systematic approach for configuring measurement system offering maximum useful information is necessary. This section give a brief outline on the research that has been done in the area of sensor placement.

In 2005, Robert-Nicoud et al. [6] proposed an iterative greedy algorithm to design a measurement system that gives maximum separation between predictions of candidate models. It follows a multiple model approach in which entropy is used to evaluate the information content at potential sensor locations. This methodology was employed on a bridge monitoring application by Kripakaran and Smith [7] in 2009. Their case study shows that at some point adding more sensors did not reduce the number of inseparable models i.e. saturation of the quantity of useful information is reached with that sensor configuration. This phenomenon was also observed in many other studies [8,9,10,11]. Papadapoulou et al [12] studied a multimodal system identification approach based on joint entropy to predict the wind characteristics around building. In the cases where correlations between the parameters are not certain, model falsification approach towards sensor placement is a promising method [13,14].

Some of the other studies, which focus on model based measurement configuration system, are as follows. Li et al. [15] looked at the relationship between the modal kinetic energy and effective independence of two measurement configuration systems for damage identification. Meo and Zumpano [16] compared six techniques for measurement system configuration to do system identification of structural vibration characteristics. For model identification on a large structure, Kang et al. [17] proposed a genetic algorithm, which they named virus coevolutionary parthenogenetic algorithm.

Irrespective of the method adopted, a good sensor placement should be applied for identification of candidate models. This paper proposes a sensor configuration methodology based on the entropy based sensor placement method of Robert Nicoud et al. [6]. This paper unlike many other works also takes into account the precision of sensors in the performance of sensor placement methodology.

3 Methodology

This paper develops an approach for designing a measurement system for continuous monitoring of a launching girder during its operational phase. The motivation behind designing such a measurement system is to arrive at an optimum number of sensors and placing them at appropriate positions such that maximum information can be extracted from the sensors. This is done in two stages.

In the first stage, an initial set of locations for sensor placement is chosen by making use of the knowledge of physical behaviour of the structure and operating conditions. Sensors should be placed at the positions where physical responses vary significantly with the change in the state of the system. The initial set of locations should also satisfy the criteria such as easy installation, provisions for maintenance, minimal interference, power supply if necessary, etc. Redundancy should also be incorporated in the design, which ensures continuous data availability even in the events of a sensor or network element failure.

The second stage in measurement system design involves evaluation of the initial set of locations for their information content. This is done by making use of the Shannon's entropy [5]. It is one of the most significant metrics in the information theory to quantify information content. Entropy measures the uncertainty associated with the random variable. Entropy H(x) of a variable x is calculated using the following equation.

$$H(x) = -\sum_{i=0}^{n} p(x_i)\, log_2 p(x_i)$$

Where $p(x_i)$ is the probability of the occurrence of an event x_i in the observation distribution. The following steps describe the procedure for evaluating the Shannon's entropy to determine the optimal sensor location.

A fundamental concept in sensor placement is the use of a population of model instances that represent different possible states of the system. A model instance is defined as the instantiation of a model class that has definite values for all the model attributes. In the case of a launching girder, a model instance represents a specific set of boundary conditions, material properties, geometry and loading. The predicted response of each model instance at every potential sensor location is determined through simulation - in the present application, through finite element analysis. The objective of sensor configuration is to find sensor locations that have maximum variations in model predictions so that after a set of measurement values are obtained, many model instances can be eliminated from the candidate set. The sensor configuration should also avoid locations that contain duplicate information content, so that a minimum number of sensors are used.

A methodology for sensor placement is shown in Figure 1. This is a variation of the methodology developed by Robert-Nicoud et al. [6]. The steps in the methodology are described below.

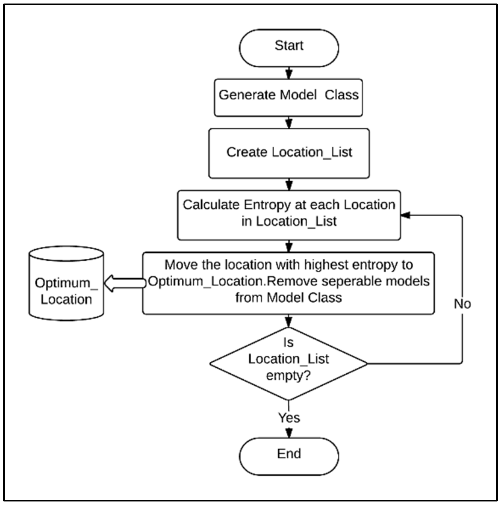

Figure 1: Sensor placement methodology-Stage 2

1. Create a list *Sub_Models* to store the subsets of models that cannot be separated by the current sensor configuration. For the first iteration, this set would contain one element that is *Initial_Modelset*
2. Create a set *Optimum_Location* to store the optimum sensor locations. At the start, the set is empty.
3. Repeat Steps 6-7 for each subset in the list *Sub_Models*
4. Create a histogram for each location in *Location_list* by grouping the model predictions into intervals. The bounds of intervals are computed such that the width of the interval is equal to the sensor precision plus modelling uncertainty. The rationale for this is that if the measured value is at the midpoint of the interval, all the model predictions within the interval could be considered as matching the measurement within the precision of measurement and modelling. The probability of an interval is the number of model predictions in the interval divided by the total number of model instances in the model subset.
5. Calculate the Shannon's entropy for each location.
6. Find the location corresponding to the maximum entropy among all the locations and model subsets. Add the selected location to the set *Optimum_Location* and remove it from the set *Location_list*. Divide each model subset into children subsets corresponding to the intervals of the selected sensor location. Each element of *Sub_Models* is replaced by the children after removing children subsets that contain only one model instance.
7. Repeat steps 5 to 8 until the list *Location_list* is empty.

The set *Optimum_Location* would contain all the positions, for the placement of sensors, which would give the maximum information content. Depending on available budget and other considerations, the sensor configuration might contain only the first few sensors in the set. In any case, if addition of new sensors do not improve the entropy, the selection process is stopped. Remaining sensors provide redundant or duplicate information that are already provided by previous sensors.

4 Sensor Placement on Launching Girder

This section discusses the placement of sensors on a launching girder. Methodology followed for the same is as discussed in the previous section. The Launching Girder (LG) is fabricated as a plate girder and spans continuously over four piers as shown in Figure 2. It consists primarily of five parts. Steel plate girder, front support, middle support, rear support and rear trolley. The steel plate girder is loaded during all the operations of the launching girder. Hence, the responses from the plate girder can be used to distinguish between different model instances. Therefore, deploying sensors on the plate girder would enable us to identify various operations of the launching girder.

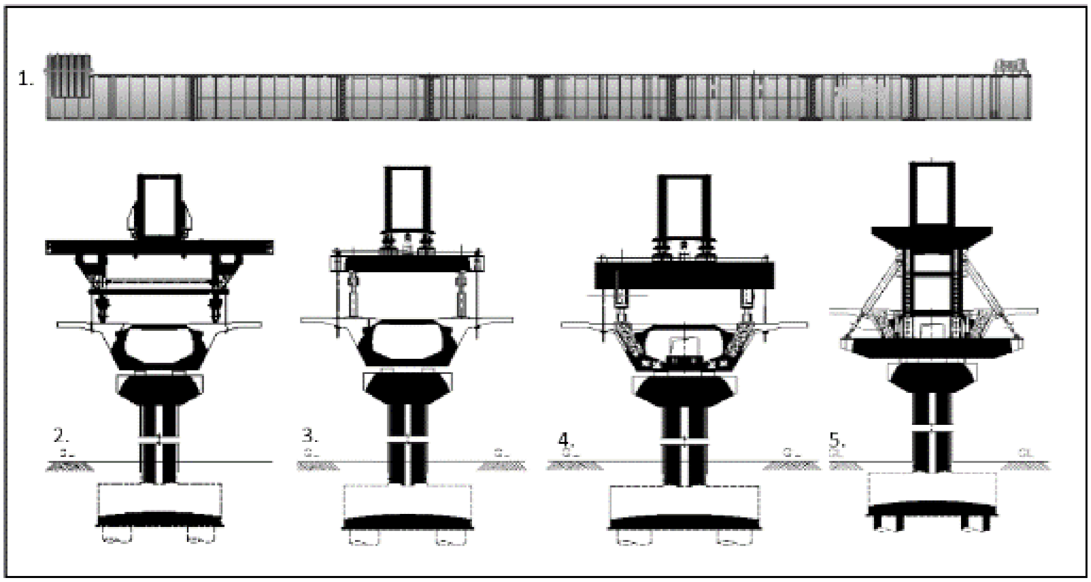

Figure 2: Parts of Launching Girder;1. Plate Girder;2. Rear Trolley;3. Rear Support; 4. Middle Support; 5. Front Support

The plate girder that is used in this study consists of eight segments. Segments are bolted at the ends to the adjacent segments. Placing sensors on either end of the each segment would help us identify the variation of stresses in that segment. Readings from the adjacent sensors can be used to identify issues with the bolted connection. Therefore, currently 16 locations have been shortlisted in the first stage. In addition to these positions, four more positions are included which corresponds to the positions where the girder is supported. Hence, 20 positions have been selected to be the initial location list. Each position have four sensors placed in it as shown in Figure 3 (Red circles denote sensors). Sensors on the top and bottom flange brings in redundancy while sensors on the web may be used to detect torque. All the sensors are fixed on the inner face of the plate girder. This arrangement protects the sensors from the interference of construction activities while providing an easy access for maintenance if in case some problem arises.

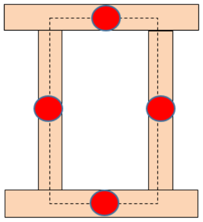

Figure 3: Placement of sensors at each location

For the second stage, a series of structural models of the launching girder are created by varying parameters, support settlement, counterweight, stiffness of the member, fixity of joints, etc. Also, these structural models should be created at different positions of the auto launching as well as segment lifting. However the current pilot study focusses on two parameters at a position of launch (22m of cantilever), they are counter weight and support settlement. The counter weight values varied from 0 metric ton to 60 metric ton in the steps of 10 ton. These parameters were chosen based on the knowledge from the construction site visits and interaction with site personnel. Both these parameters are prone to variation from design during the construction operation. Support settlements at two locations were varied from zero to 20mm. The model class contains 3087 model instances. The model instances are then analysed using a finite element analysis package Felt. Strain responses at each location are evaluated for every model instance. Strain distribution at each location is then divided into intervals where the width of the interval corresponds to the precision of the measurement. Shannon's entropy is calculated for each location and sensor positions are chosen based on the methodology discussed in the previous section. Results of the analysis are present in the next section.

5 Results and Discussion

This section presents the results of evaluations done in the previous section. The objective of the evaluations is to find the optimum sensor configuration as well as to study the influence of precision of measurement in the design of measurement configuration system. Results of the analysis is given in Table 1.

Table 1: Influence of Precision

Precision	No of Sensors	Entropy of the First sensor
0.0004	6	2.52
0.00004	4	4.68
0.000004	4	7.94

It can be observed that as the precision increases, entropy increases. From this it can be inferred that higher the precision in measurements higher the information content. Reason for this observation is that, higher the precision at a location, more number of candidate models could be separated as the interval width of histogram is reduced.

When precision is increased from 0.0004 to 0.00004, the number of sensors with non-redundant information decreases. However, when the precision is again increased to 0.000004, the number of sensors does not decrease. This proves that even if the precision is increased, a minimum number of sensors is required for effective model separation.

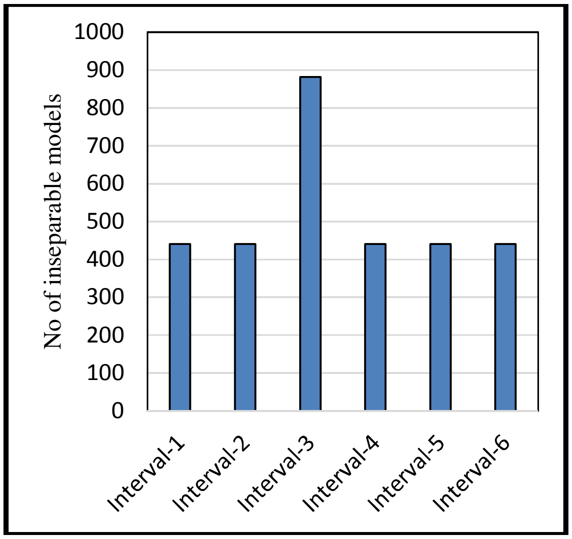

Figure 4: Distribution of inseparable candidate models; Precision=0.004; No of sensors =1

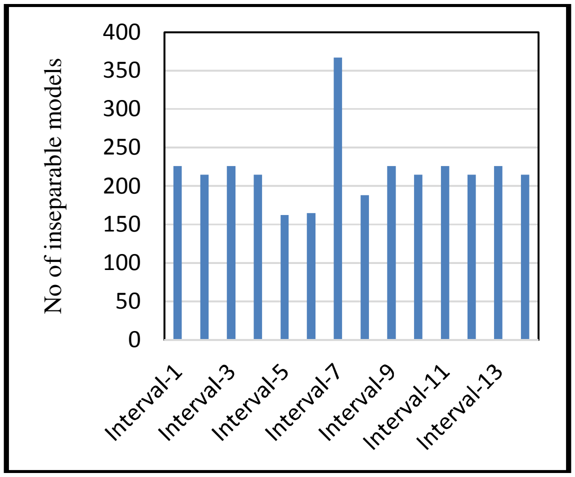

Figure 5: Distribution of inseparable candidate models; Precision=0.004; No of sensors =3

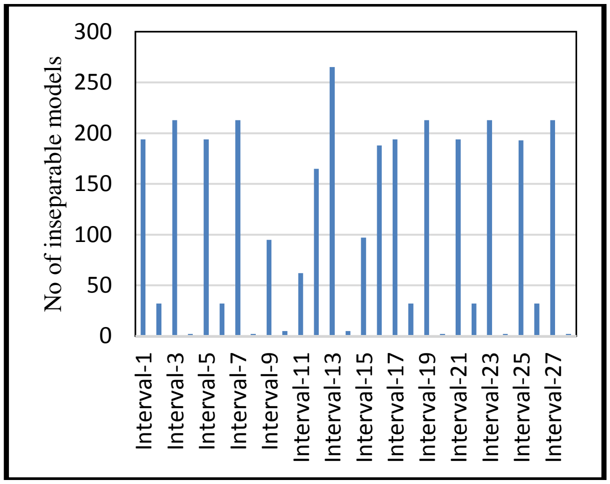

Figure 6: Distribution of inseparable candidate models; Precision=0.004; No of sensors =6

From the Figures 4,5,6 it can be seen that number of inseparable models decreases with addition of a sensor. It is observed that inseparable models are distributed over larger intervals as the sensors are being added. Thus, an increase in the number of sensors employed has an influence on the accuracy of the measurement

Table 2: Precision=0.000005
Entropy at Different locations

Location	Entropy
Element7	7.94
Element54	2.72
Element4	1.45
Element22	0.81
Element1	0

From the Table 2, it can be seen that element 1 has an entropy value of zero. All the subsequent elements also have entropy value zero. This means that the number of sensors have no influence on the information content after information saturation is reached. This observation reinforces the results of previous studies [7,8,9].

From these observations, it could be concluded that the precision of the measurement system increases the efficiency and resolution of the identifications. Increase in precision of the measurement system reduces the number of sensors to be deployed. However, a minimum number of sensors is required for efficient identification of candidate models. In addition, it can be inferred that the increase in number of sensors increases the efficiency of measurement system until information saturation is reached. Addition of sensors have no effect on the measurement system efficiency after this saturation point.

The conclusions from these observations contradict the current trend in designing the measurement systems based on the engineering experience alone. The locations arrived using such heuristic approaches might ignore sensor locations that contain rich information, which results in ambiguous interpretation. Also unsystematic approaches in measurement system design result in large amount of redundant data leading to high data interpretation costs. Out of the 20 locations chosen for experimentation, only 4-6 locations (4 corresponds to 0.000004 precision and 6 correspond to 0.0004 precision) gave non-redundant information. This reinforces the fact that extensive monitoring using large number of sensors might not be necessary to arrive at the required model separation. Therefore designing measuring system in a systematic approach is cost effective compared to the traditional approach. Decreased cost in implementation would motivate the stakeholders to include monitoring systems in their projects resulting in safer projects. The effect of precision of measurement give us a more comprehensive idea on the precision to be selected for a measurement system. It gives the decision maker a flexibility in choosing between a precise measurement system with costlier sensors or less precise system with cost effective sensors.

The current study was limited to a single scenario varying just two parameters. There is a probability that measurement system might require more sensors when all the parameters are taken into consideration. This would be dealt with in a future study and sensitivity analysis would be used to arrive at the most influential parameters to be used in measurement system design.

6 Conclusions

This paper presents an approach for designing measurement system for the continuous monitoring of a launching girder during its operational phase. The measurement system aids in deciding upon an optimum number of sensors and placing them at appropriate positions such that maximum information can be extracted from the sensors. A methodology based on Shannon's entropy was adopted in this paper to ensure optimal placement of sensors

From the observations, it is inferred that the number of sensors required and the information contents is dependent on the precision of measurement system. In addition, it is observed that, increasing the number of sensors might not increase the information content once a threshold is reached.

Further work in this area include evaluating the sensor placement algorithm with a larger model class with varying parameters. In addition, the model class should include different positions of the launching process. Validation of the methodology will be done using data from actual implementation of the sensing system on a launching girder during its operational state.

Although, the broad objective of this work is to find the state of the launching girder for the project monitoring as well as construction safety monitoring, the data from these sensors can also be used to evaluate potential operations, which can be automated, determine the service life of the launching girder, enable early identification of failures, perform design validation etc.

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