Investigating the Benefit-Cost of MEMS Application for Structural Health Monitoring of Transportation Infrastructure

M. K. Jha* and A. B. Davy**

*Morgan State University, Dept. of Civil Engineering
Baltimore, Maryland 21251, USA, mkjha@eng.morgan.edu
**Morgan State University, Dept. of Civil Engineering
Baltimore, Maryland 21251, USA, davy@eng.morgan.edu

ABSTRACT

In recent years MEMS has been widely recognized as an effective device for structural health monitoring of transportation structures, such as bridges and tunnels. It is unclear, however, whether the benefits of MEMS application far outweigh the associated cost. A quantitative approach for benefit and cost calculation of MEMS application for structural health monitoring of transportation infrastructure will be a major step forward to provide guidance to potential MEMS users. In this paper, we develop a fuzzy logic-based approach (since MEMS benefits are generally fuzzy in nature and at best, they can be quantified using fuzzy-logic) for benefit-cost calculation associated with MEMS application. Real-world case studies will be presented in future works using the proposed fuzzy-logic approach.

Keywords: MEMS, Benefit-Cost, Fuzzy Logic, Transportation Infrastructure

1 INTRODUCTION

Tools available to conduct structural health monitoring (SHM) of transportation structures have increased in number and sophistication over the past twenty years. These structures include subway and roadway tunnels, highway and railroad bridges and other above ground structures that carry our transportation network. The Transportation Equity Act for the 21st century (TEA-21) enacted for the years 1998 to 2003 and reauthorized for the years through 2009, provides a vast infusion of funds to repair and for improvement of the nation's transportation infrastructure [1]. However the majority of existing structures will not be included in the repair and rehabilitation program. Clearly, the transportation infrastructure is aging faster than it can be repaired or replaced.

Structures begin to deteriorate through wear and tear, corrosion, ever-increasing traffic and overloads, and fatigue soon after being placed into service. SHM is a strategy to consistently detect damage through cost-effective monitoring of the structure's condition early enough to schedule preventative maintenance and repair.

Three strategies have been employed in the assessment of the infrastructure condition. They are scheduled visual inspection, scheduled non-destructive evaluation (NDE) and continuous health monitoring. Visual inspection is still predominant in most jurisdictions and will be for some time to come. It cannot however detect damage until it is visible, it is time-consuming and results are very dependent on the experience of the inspector. NDE is widely supported by the Federal Highway Administration (FHWA) through its Validation Center and is mainly used on highway bridges. Ground penetrating radar, x-rays, ultrasonic testing and acoustic emission (AE) monitoring are employed to detect and monitor structural cracks and delaminations. AE monitoring utilizes detection sensors, signal transmitters and computers to process the data. NDE systems tend to be expensive, cumbersome and are generally only brought in after a problem has been determined to exist.

Health monitoring utilizes a variety of sensors, some with built in measurement, interpretation and actuation capability to provide more continuous real-time data aimed at detecting the onset of serious deterioration. Initially the tools employed in SHM were expensive, difficult to set up and maintain, and yet deterioration could still go undetected. The promise of MEMS technology in this application is that it will provide an inexpensive, durable, compact information collection, processing and storage system for use in SHM.

Many applications of MEMS applied to the transportation infrastructure have been cited in recent publications and the most efficient ones appear to be those using intelligent sensors and wireless technology. Robust, cost-effective SHM solutions are best achieved by integrating and extending technologies from various engineering disciplines [2]. The challenge of developing networking algorithms for reliable communications in a wireless data acquisition network was described in [2] and [3]. Wireless active sensors with the capability to question response data was described in [4]. Some articles ([5-6]) describe monitoring techniques that have been used in wireless sensor networks and the cost of a wireless modular monitoring system was discussed in [6].

2 BENEFIT-COST OF MEMS APPLICATION

Typically, any new application that is likely to have promise is widely embraced by people in the beginning. However, in the absence of having a clear idea about the benefits of any new technology over its cost, its long-term usability and success may be doubtful. Research suggests that while cost can be easily quantifiable, benefit quantification is often a challenging task [7]. Benefit is generally the "perception" of individuals about a commodity, which can be captured and quantified through fuzzy-logic. The first author of this article was motivated to apply fuzzy-logic to quantify the benefit of Computer Visualization (CV) in highway development since just as MEMS holds greater promise in structural health monitoring CV holds grater promise in highway development; but whether the benefits of CV outweighs its cost is generally known. In this paper we provide the theoretical framework for applying fuzzy-logic in quantifying Benefit and cost of MEMS application in structural health monitoring.

2.1 Quantifying Benefits and Costs with Fuzzy-Logic

Fuzzy logic is particularly suited for benefit and cost estimations of MEMS application for two reasons: (1) as noted earlier, while cost of MEMS application may be quantifiable it may be difficult to quantify MEMS benefits due to their fuzzy nature. At best one can describe MEMS benefit in linguistic terms (commonly known as "linguistic hedges" in fuzzy logic), such as "high," "medium," or "low." (2) by converting both benefits and costs in fuzzy form we can be assured that we are comparing apples to apples; thus, the resulting B/C ratio might make more sense since fuzzy representation of a quantity always lies between 0 and 1. A review of literature [7-10] suggests that there are very limited applications of fuzzy-logic in benefit cost assessment. Neitzel and Hoffman [8] described benefits and costs in linguistic rather than numerical terms. Our procedure of fuzzy representation of MEMS benefit and cost is similar to that developed by Neitzel and Hoffman [8] in that we also use linguistic terms in describing benefit and cost and then convert them to numerical values using triangular fuzzy numbers (described later).

Bailey et al. [11] applied fuzzy logic to quantify public perception towards visualization in highway development. However, they did not quantify visualization benefits and costs. For highway economic analysis, Benefit-Cost ratio (B/C) is generally calculated [12] to assess if a proposed development is worth undertaking. The FHWA procedure uses actual numerical values using life-cycle costs and does not consider fuzzy characteristics of benefits. Next, we derive a general fuzzy B/C calculation procedure (similar to that available in [7]), which can be applied to investigate the cost effectiveness of MEMS application in the structural health monitoring of transportation infrastructure.

3 FUZZY-LOGIC APPROACH TO B/C CALCULATION

Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth, i.e., truth values between "completely true" and "completely false." It was introduced by Zadeh [13] who defined fuzzification as a methodology to generalize any specific theory from a crisp (discrete) to a continuous (fuzzy) form. Since its inception in 1965 there has been numerous applications of fuzzy-logic in many fields where linguistic hedges often prohibit quantification. This makes MEMS benefit an excellent candidate for fuzzy-logic application.

3.1 Fuzzy Benefit of MEMS Application

In linguistic terms, benefit of MEMS application in structural health monitoring of transportation infrastructures can be characterized as "improved precision in identifying structural deterioration over time" and "reduced manual time/labor requirements for structural health monitoring." Let's introduce two sets $\mathbf{M}(x)$ and $\mathbf{N}(y)$ which represent "improved precision in identifying deterioration" and "reduced manual time/labor requirements" measured on a scale of 1-10. Intuitively, a higher number in both categories will imply "higher" increase in precision identification and "higher" reduction in time/labor requirements. The corresponding fuzzy membership functions can be represented as $\mu_{\mathrm{M}}(x)$ and $\mu_{\mathrm{N}}(y)$, respectively whose values range from 0 and 1. Thus, expected benefit, B_E of MEMS application can be expressed as:

$$B_E = 1 - \min\{\mu_{\mathrm{M}}(x), \mu_{\mathrm{N}}(y)\} \tag{1}$$

Equation (1) implies that expected fuzzy benefit of MEMS application is a combined measure of increased precision identification AND reduced manual time/labor requirements. $\mathbf{M}(x)$ and $\mathbf{N}(y)$ can be described as linguistic variables, such as "low," "medium", or "high." For consistency in numerical analysis those linguistics variables can be represented on a scale of 1-10. For example, on a 1-10 scale, "low," "medium," and "high" can be described as 2, 5, and 7, respectively. Furthermore, $\mathbf{M}(x)$ and $\mathbf{N}(y)$ can be represented as triangular fuzzy numbers with different confidence intervals [14]. A typical triangular fuzzy number is most often presented in the form:

$$\mathbf{A} = (a_1, a_2, a_3) \tag{2}$$

where a_1 is lower (left) boundary of the triangular fuzzy number, a_2 is number corresponding to the highest level of presumption, and a_3 is upper (right) boundary of the fuzzy number. The membership function of the fuzzy number **A** is:

$$\mu_{\mathbf{A}}(x) = \begin{Bmatrix} 0, & x \le a_1 \\ \left(\dfrac{x-a_1}{a_2-a_1}\right), & a_1 \le x \le a_2 \\ \left(\dfrac{a_3-x}{a_3-a_2}\right), & a_2 \le x \le a_3 \\ 0, & x \ge a_3 \end{Bmatrix} \tag{3}$$

By the similar notion assuming that $\mu_{\mathbf{M}}(x)$ and $\mu_{\mathbf{N}}(y)$ can be represented as triangular fuzzy numbers with $\mathbf{M} = (m_1, m_2, m_3)$ and $\mathbf{N} = (n_1, n_2, n_3)$, respectively. For example, if **M**=(2, 6, 10) and **N**=(2, 4, 6), then $\mu_{\mathbf{M}}(x)$ and $\mu_{\mathbf{N}}(y)$ can be expressed as:

$$\mu_{\mathbf{M}}(x) = \begin{Bmatrix} 0, & x \le 2 \\ \dfrac{x}{4} - 0.5, & 2 \le x \le 6 \\ -\dfrac{x}{4} + 2.5, & 6 \le x \le 10 \\ 0, & x \ge 10 \end{Bmatrix} \tag{4}$$

$$\mu_{\mathbf{N}}(y) = \begin{Bmatrix} 0, & y \le 2 \\ \dfrac{y}{2} - 1, & 2 \le y \le 4 \\ -\dfrac{y}{2} + 3, & 4 \le y \le 6 \\ 0, & y \ge 6 \end{Bmatrix} \tag{5}$$

The confidence intervals for membership functions $\mu_{\mathbf{M}}(x)$ and $\mu_{\mathbf{N}}(y)$ are user-specified; this has no effect on the general methodology developed here since the proposed methodology assumes a standard triangular fuzzy forms for $\mu_{\mathbf{M}}(x)$ and $\mu_{\mathbf{N}}(y)$. The confidence intervals are interpreted as being "low", "medium," and "high" and a quantitative measures of these linguistic variables are to be determined based on the characteristics of to the project to which the analysis is being applied. The assumption of triangular fuzzy numbers in similar applications can be found in Teodorovic and Vukadinovic [14] and Dompere [10].

3.2 Fuzzy Cost of MEMS Application

The different components of MEMS implementation cost can be classified as: (1) cost of hardware/software; (2) installation and setup cost; and (3) monitoring cost (which will be a recurring cost). Let $\mathbf{V}(z_1)$, $\mathbf{A}(z_2)$, and $\mathbf{R}(z_3)$ be these fuzzy costs, respectively. $\mu_{\mathbf{V}}(z_1)$, $\mu_{\mathbf{A}}(z_2)$, and $\mu_{\mathbf{R}}(z_3)$ represent corresponding membership functions having triangular fuzzy forms with confidence intervals $\mathbf{V} = (v_1, v_2, v_3)$, $\mathbf{A} = (a_1, a_2, a_3)$, and $R = (r_1, r_2, r_3)$, respectively. Using the similar analysis presented earlier about the "OR" operator the fuzzy MEMS application cost, C_M can be expressed as:

$$C_M = \max\left[\mu_{\mathbf{V}}(z_1), \mu_{\mathbf{A}}(z_2), \mu_{\mathbf{R}}(z_3)\right] \tag{6}$$

Since C_M is a combined measure of the three MEMS implementation costs noted above the use of "OR" operator is justifiable.

3.3 Fuzzy B/C Ratio

Using Eqs. (1) and (6) the fuzzy benefit-cost ratio of MEMS application can be expressed as:

$$\frac{B_E}{C_M} = \frac{1 - \min\{\mu_{\mathbf{M}}(x), \mu_{\mathbf{N}}(y)\}}{\max\left[\mu_{\mathbf{V}}(z_1), \mu_{\mathbf{A}}(z_2), \mu_{\mathbf{R}}(z_3)\right]} \tag{7}$$

4 CONCLUSIONS AND FUTURE WORK

In this paper we presented an overview of emerging MEMS application in structural health monitoring of transportation infrastructure. We developed a fuzzy benefit-cost procedure for MEMS application, which seems quite promising. It will help MEMS users in correctly assessing if MEMS application outweighs its cost. In our future works, case studies will be presented using real-world examples, cost data, and a survey of the degree of satisfaction of MEMS users.

REFERENCES

[1] Clarke, E., "TEA-21, something for everyone," ASCE Civil Engineering Vol. 68, pp. 52-55, Oct. 1998.

[2] C. Farrar, H. Sohn, M. Fugate, J. Czarnecki. "Integrated Structural Health Monitoring", SPIE, 8th Annual International Symposium on Smart Structures and Materials, Newport Beach, CA, March 4-8, 2001.

[3] J. Caffrey, R. Govindan, E. Johnson, B. Krishnamachari, S. Masri, G. Sukhatme, K. Chintalapudi, K. Dabtu, S. Rangwala, A. Sridharan, N. Xu, M. Zuniga, "Networked Sensing for Structural Health Monitoring", 4th International Workshop on Structural Control, Columbia University, Ney York, June 2004.

[4] J. Lynch, A. Sundararajan, K. Law, A. Kiremidjian, T. Kenny, E. Carryer, "Embedment of Structural Monitoring Algorithms in a Wireless Sensing Unit", Structural Engineering and Mechanics, Vol. 15, No.3, 2003.

[5] J. Lynch, A. Sundararajan, K. Law, H. Sohn, C. Farrar, "Design of a Wireless Active Sensing Unit for Structural Health Monitoring", SPIE, 11th Annual International Symposium on Smart Structures and Materials, San Diego, CA, March 14-18, 2004.

[6] J. Lynch, K. Law, E. Straser, A. Kiremidjian, T. Kenny, "The Development of a wireless Modular Health Monitoring System for Civil Structures", Proc. Of the MCEER Mitigation of Earthquake Disaster by Advanced Technologies (MEDAT-2) Workshop, Las Vegas, NV, USA, November, 30-31, 2000.

[7] Jha, M.K., "Feasibility of Computer Visualization in Highway Development: A Fuzzy Logic-Based Approach," Computer-Aided Civil and Infrastructure Engineering, Vol. 21, No. 2, pp. 136-147, 2006.

[8] L.A. Neitzel, and L.J. Hoffman, "Fuzzy Cost/Benefit Analysis." In Fuzzy Sets: Theory and Applications to Policy Analysis and Information Systems (eds: Wang, P. P. and Chang, S.K.), pp. 275-290, Plenum Press, New York, 1980.

[9] Kahraman, C., "Fuzzy Versus Probabilistic Benefit/Cost Ratio Analysis for Public Work Projects," International Journal of Applied Mathematics and Computer Science, Vol. 11, No. 3, pp. 705-718, 2001.

[10] Dompere, K.K., "Cost-Benefit Analysis and the Theory of Fuzzy Decisions," Springer-Verlag, New York, 2004.

[11] K. Bailey, T. Grossardt, and J. Brumm, "Enhancing Public Involvement Through High Technology," TR news, pp. 16-17, May-June 2002.

[12] FHWA, "Economic Analysis Primer," U.S. Department of Transportation, Federal Highway Administration, Office of Asset Management, Washington, D.C., 2003.

[13] Zadeh, L. "Fuzzy Sets." Information and Control, Vol. 8, pp. 338-353, 1965.

[14] D. Teodorovic, and K. Vukadinovic, "Traffic Control and Transportation Planning: A Fuzzy Sets and Neural Networks Approach," Kluwer Academic Publishers, Norwell, MA, 1998.