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# Customized Sensors for Structural Health Monitoring in a Train System

*Seung Ki Moon[1], Yuhua Li[2], Samyeon Kim[3], Yu En Tan[3], Zhong Yang Chua[3], and Teck Hui Ngo[4]

[1,2,3] *School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, 639798*
[4] *SMRT Trains Pte Ltd, Singapore, Singapore, 579828*
[*] skmoon@ntu.edu.sg

## ABSTRACT

For structural health monitoring, the identification of potential failures is able to understand and predict the impact of component and system risks. Additive manufacturing (AM) or 3D printing has been penetrating deeper and wider into various industries, due to its free-form, cost effectiveness, free-tooling capabilities, and mature processes. Electronics is also a huge and very promising application field for multi-material AM technologies. This paper introduces a method to develop customized sensors for structural health monitoring by integrating 3D printing technologies and the existing sensing technologies. In the proposed method, failure mode effect and analysis (FMEA) and System Dynamics (SD) are used to determine critical components and potential failures. Finite effective analysis (FEA) is applied to identify and understand component failure mechanisms. FEA can provide the useful engineering information of structural health conditions, such as stress, strain and heat transfer process. And, then we use the results from the FEMA, SD, and FEA to determine the types and positions of the customized sensors for the structural health monitoring. To demonstrate the usefulness of the proposed design method, Aerosol Jet technology is applied to fabricate the proposed sensors for the health monitoring.

## 1. INTRODUCTION

Structural Health Monitoring (SHM) is important to prevent catastrophic failures and the process of gathering data from sensors incorporated into the structure. The obtained data will be analyzed to validate the health of the structure based on the sensors. Health is the ability to perform and maintain the structural integrity throughout

[1] Assistant Professor
[2] Research Fellow
[3] Graduate Student
[4] Executive Engineer

the entire lifetime of the structure (Farrar and Worden 2010). The one of challenges in SHM systems is to remain effective despite changing boundary conditions of complex structural configurations. And, durability requirements should be as another major challenge for the SHM systems especially when integrating them onto the structure itself. This prevents false data from being collected due to unintentionally damaged sensors by mechanical loads and not that the structure itself was damaged (Baere, et al. 2014). Additionally, the required sensing system properties should be defined before field deployment and if possible, ensure that the sensors will not be damaged when deployed in the field (Ciang, et al, 2008). Also, the SHM systems need to determine the lowest number of parameters to be monitored for understanding and predicting the impact of component and system risks.

Additive manufacturing (AM) or 3D printing has been penetrating deeper and wider into various industries, due to its free-form, cost effectiveness, free-tooling capabilities, and mature processes. AM technologies are currently being developed for applications in the aeronautical, automotive, energy, mechanical engineering and medical sectors (Yao, et al. 2016). AM technologies can be applied to a wide variety of feed materials including metal alloys, polymers and ceramics brought about the creation of functional, low volume, highly complex parts (Ko, et al. 2015). Electronics is also a huge and very promising application field for multi-material AM technologies.

The objective of this paper is to propose a method to develop customized sensors for SHM by integrating 3D printing technologies and the existing sensing technologies. In the proposed method, failure mode effect and analysis (FMEA) and System Dynamics (SD) are used to determine critical components and potential failures. Finite effective analysis (FEA) is applied to identify and understand component failure mechanisms. And, then we use the results from the FEMA, SD, and FEA to determine the types and positions of the customized sensors for SHM. Based on the information of designing sensors, Aerosol Jet technology is applied to fabricate the proposed sensors for the structural health monitoring.

The remainder of this paper is organized as follows. Section 2 describes the proposed method to develop customized sensors for the health monitoring. Section 3 shows a case study for applying the proposed method to fabricate a customized sensor. Closing remarks and future work are presented in Section 4.

## 2. CUSTOMIZED SENSOR DESIGN METHOD

Figure 1 shows the proposed method to develop customized sensors for structural health monitoring by integrating failure information, sensor design methods, and additive manufacturing technologies. The proposed method consists of four phases: (1) analyse failure information, (2) identify failure modes, (3) design the customized sensors, and (4) fabricate the proposed sensors. In the initial phase, a system for monitoring is selected to analyze the failure information of the system using failure modes and effect analysis (FMEA) and system dynamics (SD). The second phase is to identify the failure modes of the system using FEA and simulation. The structure design parameters are identified based on the failure modes. The parameters will be integrated with the design parameters of the customized sensor using design structure matrix. And then, Aerosol Jet technology is used to fabricate the proposed sensor.

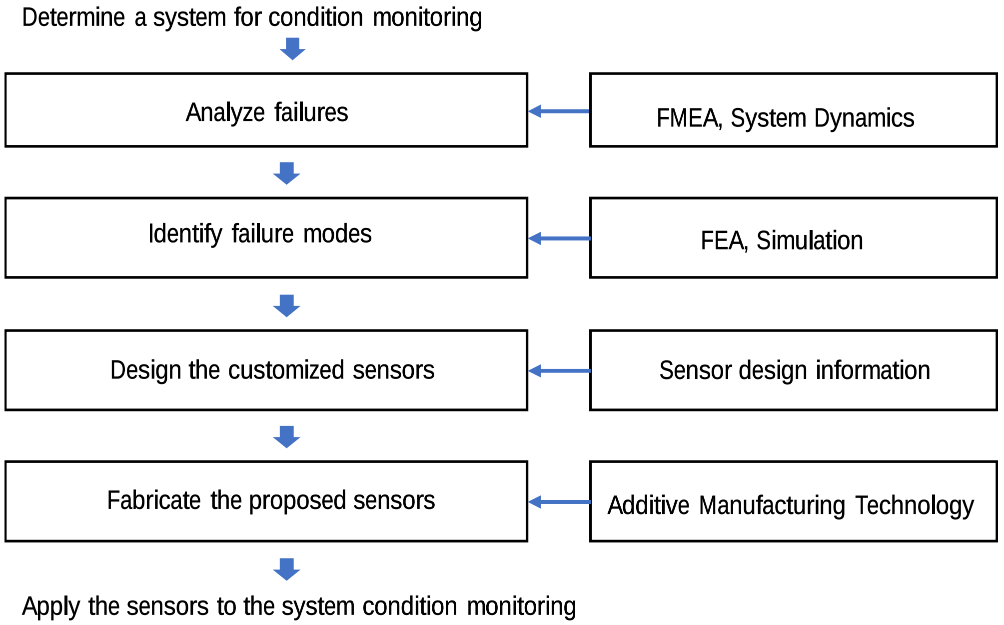



Fig. 1 The proposed method for designing customized sensors using AM

*2.1 Failure Analysis and Identification*

In this paper, the functional diagram with FMEA is introduced to understand functional relationships and determine the critical components and failure modes based on comprehensive diagram in a system (Bowles and Pelaez, 1995). FMEA is a formalized analytical approach and has been applied to improve the reliability and quality of a product by identifying, analyzing and eliminating potential failures and risks (Stamatis 2003). FMEA investigates all potential failure resources, and then determines the severity of the consequences of the failure based on a weighted score (Teng and Ho 1996). The traditional FMEA utilizes a risk priority number (RPN) to assess the risk level of each failure mode of a component.

SD is applied to model dynamic behaviour based on real situation and predicted a tendency of a time-based failure modes and effects. SD is one of simulation modeling to provide a visual tool for approximating real life behavior on the basis of causal structure (Lewlyn, et al. 2006). SD provides an effective way for testing scenarios with various factors and uncertainties (Lee, et al. 2015). Modeling the SD has mainly focused on discovering causal relationships between individuals and representing feedback processes (Sterman 2000). However, it is difficult to construct the model because knowledge from in-depth understanding of a system is required.

FEA is a numerical method that is a commonly used method for multi-physics problems and has been used in various industries increasingly. In this paper, FEA is applied to identify and understand failure mechanisms for a system. FEA can provide the useful engineering information of structural health conditions, such as stress, strain and heat transfer process.

### *2.2 Customized sensor design*

This research includes the development of a customized sensor that can be deployed on mechanical components for collection and transmission of health data. Sensors are customized based on the parameters to be monitored for the mechanical systems such as temperature, vibration, stresses or strains. Contrary to traditional subtractive or formative manufacturing technologies, Additive manufacturing (AM) produces parts through successive layer-upon-layer fabrication processes. Tool-less and layer-upon-layer nature in AM provide designers with new opportunity for customization using its unique design freedom that the traditional processes cannot provide it (Gibson, et al. 2014). In this situation, surface integration of additive manufactured sensors on customized parts must be able to deal with the specific characteristics of the part features, typically non-planar 3D surfaces (Lehmhus, et al. 2016). Therefore, the dependencies between the structure's and sensor's geometrical characteristics are analysed from the initial design phase to explore the new design space provided by additive manufacturing.

The proposed design process is shown in Figure 3. The process starts with two parallel sub-processes: analysis of part's and sensor's geometrical design parameters. The part's geometrical parameters are based on the part behavioural information to be monitored resulting from FMEA, SD, and simulation. Once the results specify the part features on which sensors are deployed, the geometrical characteristics such as non-planar 3D surfaces or certain complex shapes are analyzed and represented as a set of design parameters. In parallel, the designers and developers need to conduct the analysis of sensor's geometric forms based on the required sensor performances for the part behaviour monitoring. The additively manufactured sensor geometry can differ from the traditional ones while being individually optimized for the customized surface features and part behaviours. Therefore, in this phase, benchmarks on the traditional sensor designs can be applied to highlight which features can be individually modified or newly designed. After the form features of the part and sensors are represented as design parameters, design structure matrix (DSM) can be applied to analyse the form dependencies between them (Browning 2001). Based on the form dependencies, the process finally achieves the customized sensor design.

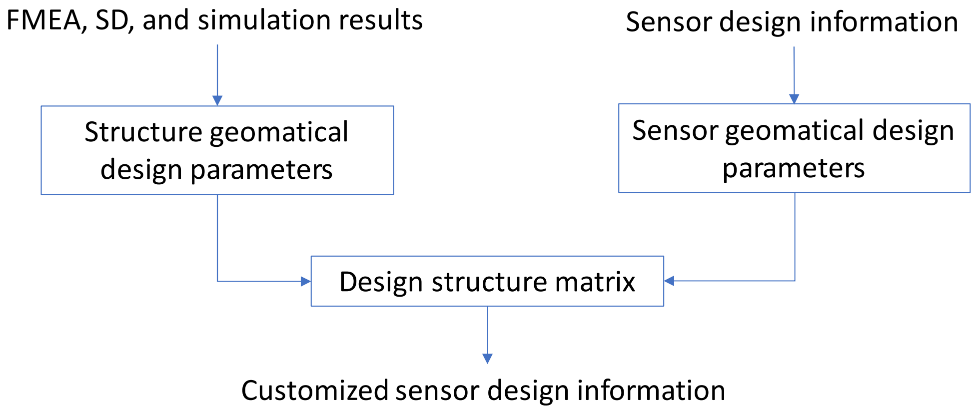



Fig. 2 The proposed process for generating customized sensor information

By extending the concept of DSM, we propose a sensor- and structure-based parameter DSM to establish most of the customization opportunity offered by AM-enabled design freedom. The component structure with additively manufactured sensor is a physical structure-system unit. While, we identify the maintenance requirements based on functional diagram with FMEA, FEM, and SD in the other processes, the main analysis of the DSM focuses on the interactions and relations between the sensor and structure design parameters for the further development of additively manufactured customized sensors.

*2.3 Additive manufacturing technology for the customized sensors*

Additive Manufacturing (AM) simplifies the process of fabrication of electronic devices and makes it more cost effective than traditional PCB-based manufacturing techniques. This is because the same materials are used for different parts of a circuit, such as materials for contacts and interconnects of the circuit. With AM, using the same source of material, multiple components can be printed at the same time. The number of processing steps is reduced (Ostfeld, et al. 2015). Additionally, the need for subtractive processes such as photolithography and etching becomes obsolete therefore the complexity as well as materials wastes are reduced (Kessler, et al. 2005). Aerosol Jet technology allows a process to produce depositions with complex features and high resolution which can directly print functional electronic circuitry and components onto substrates which have features in different planes and at low temperatures (Maiwald, et al. 2010). Aerosol Jet technology uses aerodynamic focusing technology to produce electronic and physical structures with feature sizes even down to 5 microns and also wide area conformal coating.

## 3. CASE STUDY

In this paper, we use a case study involving an air compressor to validate the usefulness of the proposed method for developing a customized sensor using Aerosol Jet technology. The compressor is a type of screw compressors supplying compressed air to power the pneumatic system on a train. The scope of this case study involves the use of FMEA and SD to evaluate critical components and failure modes of the compressor. Table 1 shows an example of the result of FMEA conducted on an air compressor system in a train. And the final risk rating of the identified failure modes can be determined. And then, the functional diagram with FMEA was developed to understand functional relationships in the screw-type air compressor system as shown in Figure 3.

We added failure mode flow with alternate long and short dash line, failure effect with hexagonal box, and failure effect propagation with blue dashed arrow that has not been considered in the conventional functional diagram. The failure effect propagation can also be represented in the Figure 3. And, we determined that oil leakage from the temperature control value and oil filter can affect overheating of compressor portion based on the interview with train engineers. The functional diagram with FMEA is to understand functional relationships in a system and help a team determine critical components and failure modes based on the comprehensive diagram.

To model SD, we assumed a scenario based on the real problem, which is that oil level in the compressor portion has to be maintained with sudden level for normal operation without failures. The stock and flow diagram as shown in Figure 4 is visualizing a compressor portion system with circulating oil, refilling oil when oil in the compressor portion is lower than threshold oil level, and leaking oil.

Table 1 FMEA result of an air compressor system

| Item | Function | Potential Failure Mode | Potential Effect(s) of Failure | Potential Cause of Failure | Current Prevention Measures | Recommended Action |
|---|---|---|---|---|---|---|
| Motor | It serves as the air compressor driver | Motor fails to run | Air Compressor will not start. Train will stay stationary | Loss of power | Standby motor | Scheduled Preventive Maintenance |
| | | Fails off while running | Air Compressor will shut down immediately and the train will stop immediately | Control signal lost | Standby motor | Scheduled Preventive Maintenance |
| | | Operates at degraded torque/rotational speed performance (runs backward, too fast, too slow, etc.) | Overheating might occur. Train performance will be affected | Overload protection trip-off | Standby motor | Scheduled Preventive Maintenance |

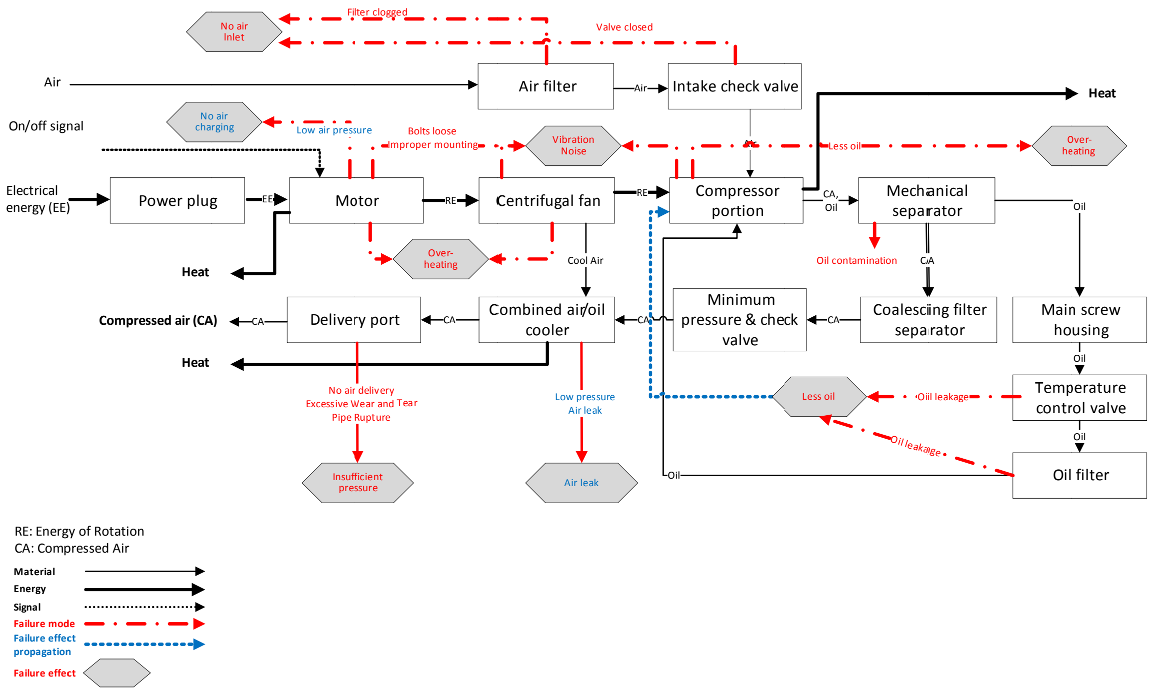


Fig. 3 Functional diagram with FMEA for an air compressor

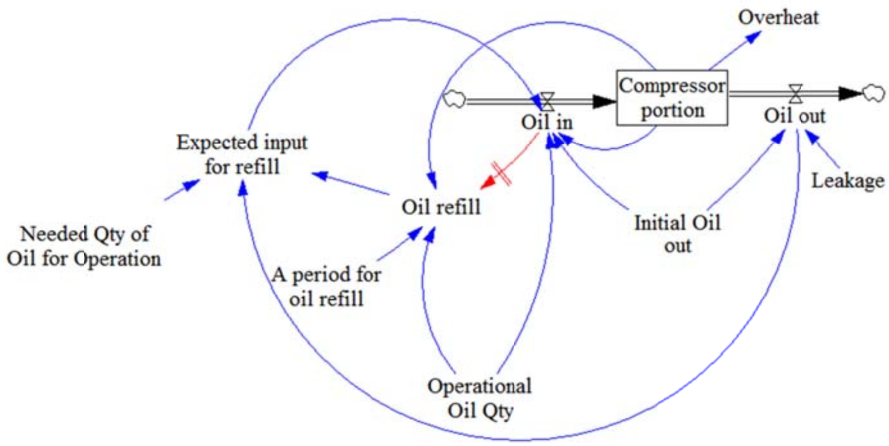


Fig.4 Stock and flow diagram of system dynamics

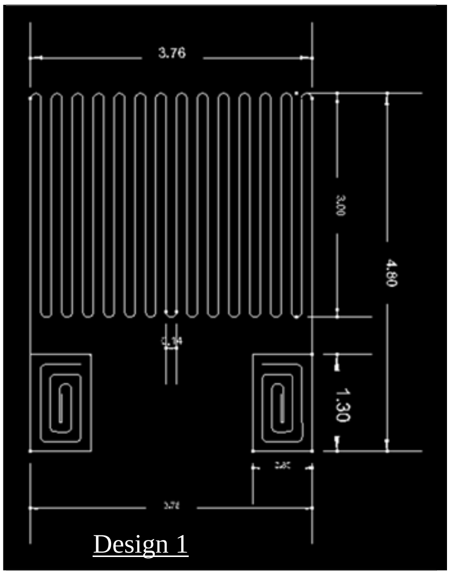
Considering the cost and the difficulty in using the experiment measurement to test each one of the components in the air compressor system, FE method was used to simulate the real conditions in the system. The FE thermal analysis of a similar component has been done to simulate the rotors in the screw type air compressor. The FE analysis provided the useful engineering information such as the stress, the strain and the heat transfer process, and the potential location of the sensors can be provided through the contours plots.

Based on the customized design information, Optomec aerosol jet printer was used to deposit Clariant PRELECT® TPS 50 G2 silver nanoparticles ink on to the substrate. The silver nanoparticles ink was placed in the ultrasonic atomizer that creates a dense mist filled with droplets between 2- 5 µm in diameter. The aerosol mist is then sent to the nozzle where the ink is focused and printed onto the substrate by a sheath gas. The process parameters used in the aerosol jet process are shown in Table 2.

Table 2. Processing parameters used in Optomec®

| Machine Process Parameters Setting | Values | Unit |
|---|---|---|
| Atomizer Current | 0.38 | A |
| Atomizer Gas Flow | 25 | SCCM |
| Process Speed | 5 | mm/s |
| Rapid Speed | 25 | mm/s |
| Nozzle Diameter | 150 | $\mu m$ |
| S MFG | 12 | |
| UA MFG | 35 | |
| PA MFG | - | |
| EX MFG | - | |
| Heater Temperature | 70 | ˚C |

Figure 5 shows the proposed two strain gage designs with customized sizing and the use of Aerosol Jet 3D printing technology. The strain gage will be directly printed onto the structure. Strain gage's parameters in Table 3 were determined based on a sensor-and structure-based parameter Design Structure Matrix (DSM). Figure 6 shows the fabricated strain gauges using Aerosol Jet technology.



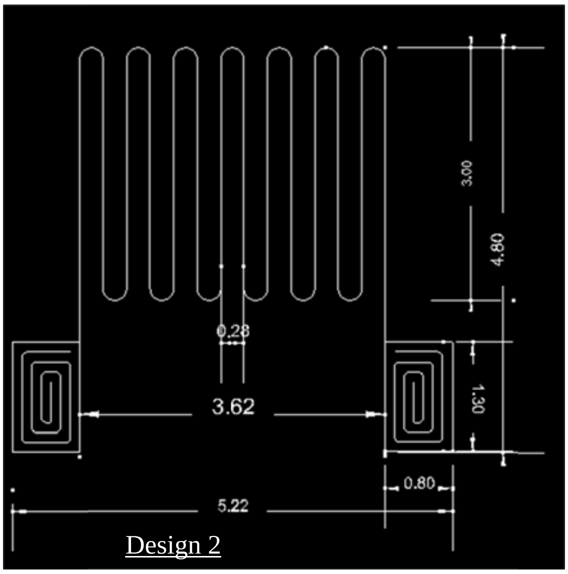




Fig.5 Customized designs for strain gauge

Table 3 Design parameters for the customized sensors

| Design | 1 | 2 |
|---|---|---|
| Edge Type | 0.14mm Diameter Semi-circle | 0.28mm Diameter Semi-circle |
| Minimum Gap Distance | 0.14mm | 0.28mm |
| Height | 3.00mm | 3.00mm |
| Total Size (Height x Breadth) | 4.80mm x 3.76mm | 4.80mm x 5.22 mm |
| Line Thickness | 0.151mm | 0.151mm |

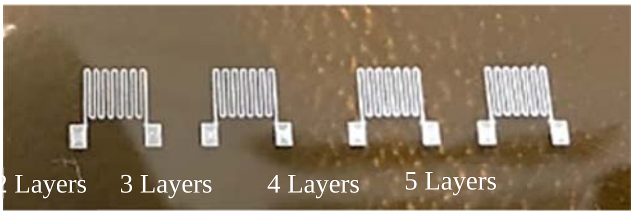


Fig. 6 The fabricated strain gauges

## 4. CLOSING REMARKS AND FUTURE WORK

In this paper, we introduced a design method to develop customized sensors for structure condition monitoring using an additive manufacturing technology and the existing sensing technologies. Functional diagram with FMEA was used to understand functional relationships in a system and helped designers determine critical components and failure modes based on comprehensive diagram. SD was used to determine critical factors and components for failure modes and effects. Through FEA, the potential location of the sensors can be provided and this analysis can be used to support our customized design for the sensors. Aerosol Jet technology and its process parameters were used for fabricating the proposed customized sensor.

The proposed methods and technologies will provide a structure condition monitoring system that is customizable and easily adapted by potential applications. For future work, the research will be focused on applying simulation approaches to understand the failure modes of a system, developing an algorithm for predictive decision making and recommendation of condition based maintenance actions based on data collected from the proposed customized sensors.

## ACKNOWLEDGMENT
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