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Approach towards sensor placement, selection and fusion for real-time condition monitoring of precision machines

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ABSTRACT

Moving mechanical parts in a machine will inevitably generate vibration profiles reflecting its operating conditions. Vibration profile analysis is a useful tool for real-time condition monitoring to avoid loss of performance and unwanted machine downtime. In this paper, we propose and validate an approach for sensor placement, selection and fusion for continuous machine condition monitoring. The main idea is to use a minimal series of sensors mounted at key locations of a machine to measure and infer the actual vibration spectrum at a critical point where it is not suitable to mount a sensor. The locations for sensors' mountings which are subsequently used for vibration inference are identified based on sensitivity calibration at these locations moderated with normalized Fisher Information (NFI) associated with the measurement quality of the sensor at that location. Each of the identified sensor placement location is associated with one or more sensitive frequencies for which it ranks top in terms of the moderated sensitivities calibrated. A set of Radial Basis Function (RBF), each of them associated with a range of sensitive frequencies, is used to infer the vibration at the critical point for that frequency. The overall vibration spectrum of the critical point is then fused from these components. A comprehensive set of experimental results for validation of the proposed approach is provided in the paper.

1. Introduction

With the rapid developments in modern automation and manufacturing technology, automated machines used in the manufacturing of high-end consumer products are getting increasingly sophisticated to allow the efficient production of high quality products at large quantities to achieve economy of scale. As the level of complexity increases, the costs due to inaccuracies and downtimes arising from tool wears and extraneous factors will also increase. As such, to mitigate against such scenarios and costs, there are high demands for more systematic, efficient and effective real-time diagnostics and techniques that monitor machine operational conditions.

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Common scenarios leading to loss of machining accuracy include excessive vibrations from the degradation of machine tools following the loss of surface material during machining processes, or vibrations and new dynamics induced from faults from other parts of the machine. Persistence with these extraneous disturbances may lead rapidly to low quality and unacceptable products, and/or machine faults. These unwanted vibrations can also directly or indirectly affect the overall machine performance and hence, the manufacturing efficiency. However, these scenarios can be mitigated if the conditions are well monitored and even when the tool is no longer in the optimal condition, other operational parameters may be accommodated to still enable some degree of productive operations. Thus, an appropriate mean of machine monitoring can enhance both manufacturing efficiency and end product qualities [1].

An established practice of detecting extraneous disturbances relies on human sensory [2] response to their occurrences, in which an experienced technical personnel observes the machine operational characteristics such as those in the form of the sound and vibration generated. If abnormality is observed, a certain degree of correction can be performed via manual adjustment of machine parameters such as machining speed and force to restore some operational order. However, such a method is heavily dependent on the experience of the technical personnel and the acquired skills are typically in the form of mental models which are difficult to be documented and imparted to a new personnel, not to mention replicating the skills set onto an automation system. This phenomenon is due mainly to the complex nature of the monitoring process involved multiple factors. Thus, an objective and systematic diagnostic approach is highly desirable which can perform beyond the level of current practice and amenable to continuous and online implementation.

Various condition monitoring methods for unmanned manufacturing systems employing machining processes have been proposed and evaluated in the past, but evidence of these methods being adopted at the downstream is obscure. The main reason, as aforementioned, is the complexity behind the large scale process which is affected by multiple factors and the constraints of machine to allow the retrofitting of multiple sensing and integrating them along with the control and intelligence into a single functional unit. Generally, published methods can be categorized into two main groups: (1) Direct method, which requires the machine tool to be removed from the machine, or the machine operations to be suspended in order to physically evaluate machine status such as the volumetric loss of the tool. Thus, this method is not suitable for continuous and real-time operations. (2) Indirect method leverages on the measurement of the machining variables such as force, vibration, acoustic emission and power dissipation during the machining process to compare them against normal operational signatures. The indirect method, while favorable from a practical perspective, is rather sensitive to machining parameters such as material variations and tool conditions, and a robust model is often necessary at the core of the approach. For continuous and real-time applications, the indirect approach has been the focus of various research works and they are mainly based on the algorithm of signal processing, sensor fusion and neural network [3–11].

The indirect method of machine monitoring relies significantly on the sensory system deployed to monitor the machine conditions. The important factors determining the effectiveness of such a scheme are (1) Sensor placement methodologies and (2) Sensor selection and fusion to combine the multitude of sensory information available via intelligent signal processing algorithms to yield a machine condition indicator. Unless a good physical understanding of the machine is available, the selection of good sensor locations is mainly driven by engineering judgement and iterated with the data collected. Furthermore, it is rare that a specific location is optimal for detecting all types of disturbances, so that it is important to know the conditions under which a location is superior to another, in terms of yielding the appropriate information for machine monitoring. In order to obtain a comprehensive monitoring coverage with a limited number of sensors, one of the important issues must be considered is for evaluation of the relative effectiveness of various locations [12–25].

Extensive research works have been conducted in these areas, with various techniques developed to evaluate and quantify the performance. Salama et al. [12] proposed using modal kinetic energy (MKE) as a mean of ranking the importance of candidate sensor locations. There have been several variants of this scheme based on the average kinetic energy and weighted average kinetic energy proposed by Chung and Moore [13]. Li et al. [14,15] studied the relation between the effective independent (EI) method and the MKE method. Kammer [16] proposed an iterative method using the EI method, based on the maximization of the determinant of the Fisher Information Matrix (FIM), to give a ranking to the sensor locations. FIM has been extensively used because it can be built from a finite element model of the machine structure or from the results of an experiment model [17–20]. Other performance indices that can be applied to sensor location evaluation are Error Covariance Matrix [21,22], Information Entropy [23], Hankel Singular Values [24], and Controllability and Observability Gramian [25].

In this paper, we propose an approach towards sensor placement, sensory set selection and fusion for continuous and real-time monitoring of machine conditions. The approach is scalable and it employs an architecture that is modular and amenable to parallel processing of incoming data to remain viable and sustainable for real-time applications without requiring large scale retrofitting to the system. A common machine monitoring problem is adopted to serve as the background problem for illustration of the framework and experiments, though the framework presented is applicable to other monitoring problems. The main objective under the problem posed is to use a minimal number of vibration sensors mounted at key locations of a machine to infer the actual vibration spectrum at a critical point, where direct mounting of sensors at this location is not feasible. An example of such a critical point is at the tool tip of a machining center. The quality of the end-product is very much dependent on the tool condition and hence, real-time monitoring of the vibration spectrum at the critical point is necessary to allow various control and mitigation measures to be invoked when needed. The sensor placement locations are selected on the basis of a moderated sensitivity indicator which fuses the location sensitivity to a

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