A LOW COST FLYING ROBOT FOR DEPLOYING AD HOC WIRELESS SENSORS IN A MANUFACTURING ENVIRONMENT

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ABSTRACT

Ad hoc wireless sensor networks are gaining popularity for use in manufacturing environments. As a result, there is a need for for a safe and rapid deployment technique to place sensors in desired locations without interrupting shop floor operations. To solve this problem, a flying robot has been developed to deliver a Bluetooth wireless sensor unit to a specified location. The robot does not interfere with machining operations and is operated by a remote user. The system is demonstrated by deploying an acoustic emissions sensor on an end millling platform. The system is also demonstrated to escape radio path interference. Data is recorded and the results are discussed.

INTRODUCTION

Due to the cost and limitations of current commercial sensor systems, machine tool manufacturers have been hesitant to accept sensor integration techniques. Although work such as [1] explores inexpensive machine tool sensor solutions, there are numerous factors beyond sensor cost and performance. For machine tool manufacturers, the scalability of sensor systems is a major concern. For this reason, the popularity of wireless sensor networks is growing for condition monitoring in manufacturing environments [2,3]. Recent work by [4] has shown the feasibility of wireless tool tip temperature monitoring during end milling. Similarly, high bandwidth data acquisition for end mill tool tip vibration has been demonstrated using commercially available Bluetooth audio transceivers [5,6].

In many cases, despite wireless capabilities, it may be difficult to justify the expense of installing fixed sensor systems on production machinery. In addition to sensor hardware and maintenance overhead, manufacturers cannot spare machine time retrofitting fixed sensor systems onto existing metal cutting equipment. Moreover, fixed location wireless sensors can suffer from changing electromagnetic path interference common on a manufacturing shop floor [7].

Therefore, a system must deploy and relocate wireless sensors without installing permanent hardware on a machine tool or causing downtime. However, for safety reasons, it is impossible to manually place or relocate a sensor in an operating machine tool platform. Ideally, the sensor deployment could be conducted with a small low cost robot and the machine tool would not have to stop operating during sensor deployment. Since a robotic sensor is deployed into dangerous live manufacturing environments, it's cost must be extremely low. Despite a low cost, the robot-sensor-transmitter system must be reusable and capable of transmitting high bandwidth machining data to a central control location.

Modern semiconductor technologies have enabled the mass production of toy RC models with highly advanced integrated control systems [8]. Many of these models are built with programmable control interfaces and high bandwidth communications protocols. In a recent example by [9], a popular commercial robotics kit was augmented with a Bluetooth interface for remote control and data feedback.

In many cases, the capabilities of remote controlled or autonomous robots far exceeds the requirements for deploying a wireless sensor in a manufacturing environment. For example, robotic data collection units have been demonstrated by [11] for use in complex coral reef terrain. Similarly, advanced machine interface, control, and feedback techniques are reviewed by [10] for human service robotics.

This work shows the development and testing of a remote controlled flying robot capable of delivering an acoustic emissions sensor inside the machining envelope of an end mill without interfering with the machining process.

BACKGROUND

The price to performance ratio is a dominant metric for evaluating the success of this work. Altogether, the components used to construct the transmitter, sensor, and robot platform retail for under $20. Although constrained by this cost, the system completes the following tasks:

- Fly from a control location on the shop floor
- Land within the machining envelope of an end mill
- Stream acoustic emission data to a PC receiver located at the control location

By selecting a variety of commercially available components, a system has been developed to satisfy these project goals while maintaining a reasonable cost.

Data Transmission Method

In an end milling system, significant challenges to wireless bandwidth may exist from motor noise. During the machining process, spindle and bed motors generate a wide and continually changing spectrum of interference. This may increase the difficulty of wireless transmission with fixed frequency or amplitude methods. The problem can be approached in two ways: Characterizing the spectrum of motor noise and designing a transmitter to avoid it for a particular milling process, or, employing an active noise avoidance scheme such as frequency hopping spread spectrum (FHSS). Because of the multitude of mill configurations and processes, it is desirable to choose the second technique, since it is most amicable to generalization.

Since 1998, FHSS techniques have been commercially standardized for use on the license-free ISM band (2.4-2.4835 GHz). This standardization has been motivated by attention from the communications hardware industry, with one particular standard being defined through the Bluetooth Special Interest Group [12]. High quality audio transmission has been at the forefront of this technology with interoperability between all Bluetooth audio devices being based on the Audio Distribution Model [13]. Transmission bandwidth requirements conform to mandatory sampling requirements of 44.1 and 48.0 kHz. These rates are enforced for the benefit of the transmitter by the receiver device [13].

For this work, a commercially available 16 bit audio transmitter is used. The transmitter circuit is modified from a Jabra BT135 transmitter (retail cost approximately $8). This transmitter contains the necessary transceiver hardware and A/D circuit to transmit a resistive load. This transmitter conforms to the published specifications in [13] and is capable of sending a audio signal to the Bluetooth receiver at 48.0 kHz. The analog signal conditioning circuit on this particular transmitter has a high frequency rolloff with a corner frequency of 3250 Hz. This is observed in preliminary testing of the device and exists to prevent aliasing in the A/D. The effective frequency bandwidth of this transmitter is approximately 10 Hz to 3250 kHz.

Sensor

The acoustic emissions sensor used for this work is a Hosiden KUB2823 electret condenser microphone. This microphone was selected since it has a flat frequency response to 5 kHz, sufficient for capturing end milling frequency content. Figure 1 expresses the sensitivity of the electret condenser microphone in terms air pressure fluctuation, dBV/pa (dBV/10µbar).

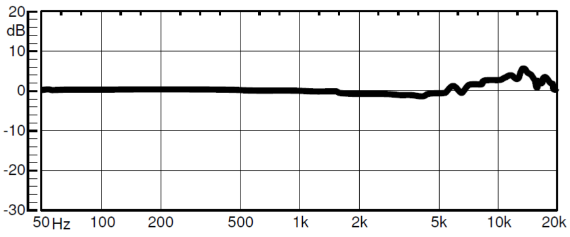


Figure 1: Air Frequency Response [14]

This electret condenser microphone is used according to the manufacturer specifications and, unlike [1], does not require recalibration.

Robot Platform

As with the Bluetooth data transmission method, the robot mechanical platform is composed of a low cost commercial product, modified to satisfy the task. A Taihengbao "Combat Force Super Helicopter" model was selected for this project (approximate retail cost $10). This model provides the essential mechanical parts to hover, maneuver, and land at a destination. The model includes a bi-motor system for lift and trim stabilization. For a demonstration of this system, refer to [16]. The model also contains a prop pitch gyroscope for lift regulation. This gyroscope is essential to controlled operation in a confined space and provides 'overdamped' lift behavior. Nonessential and aesthetic components were discarded from the model to save mass necessary to lift the sensor and transmitter package.

ROBOT AND SENSOR SETUP

The robot-sensor-transmitter system was fabricated by modifying the chassis of the helicopter model to accommodate the Bluetooth transceiver board. The drive control of the helicopter was modified to accept a 3.7 volt input directly from the transmitter's lithium polymer battery supply. Since the transceiver hardware is supported on a 3 volt regulator, voltage fluctuation from motor draw does not affect transmitter performance. Subsequent to the construction and installation of the sensor system, the model required balancing to maintain a stable center of gravity. Figure 2 shows a detailed illustration of the completed system detailing the hardware components

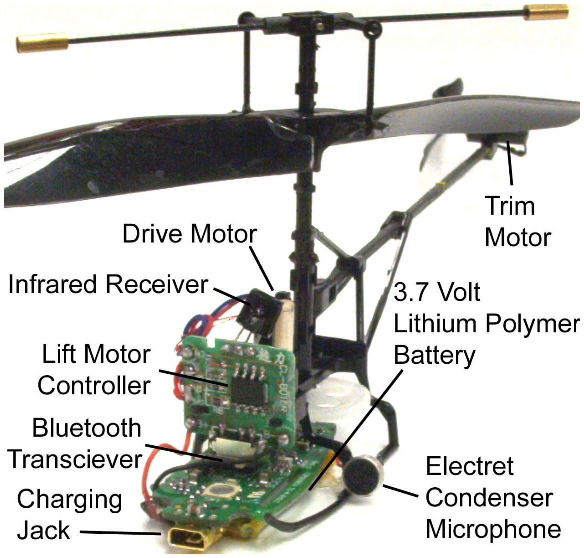


Figure 2: Sensor Robot Anatomy

EXPERIMENTAL SETUP AND DEPLOYMENT

The robot launch and control platform was located 6 meters from the destination inside a Fadal 3 Axis milling machine. A stainless steel workpiece was mounted on the bed of the milling platform with sufficient surface area for the robot to land. Figure 3 shows the laboratory setup and flight path from the control location. The robot was manually controlled through an infrared interface capable of sending signals to

Figure 3: Laboratory Flight Path

modify trim and lift. The robot operator required a training period before deploying the sensor to the target destination. Since the control behaviors of the helicopter were unmodified, the model was capable of control maneuvering through perturbation of the trim motor and lift. Although the geometry and mass of the commercial robot kit is modified to house the sensor and Bluetooth transmitter, the standard controller behavior is sufficient. The control tolerance of the robot allows the acoustic emission sensor to be positioned within ten centimeters of the cutting tool, uninhibited by obstacles. Figure 4 details the location of the robot with respect to the milling tool-workpiece interface.

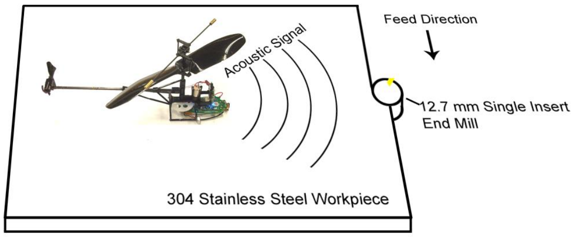


Figure 4: Experimental Setup

EXPERIMENTAL RESULTS

After training an operator to deploy the robot into the milling envelope, verification of the system was conducted during a cutting operation. A linear path cutting test was conducted with a 12.7 mm (½”) insert end mill tool, feed rate of 254 mm/min (10 in/min), and a spindle speed of 3819 RPM. The data is inspected for information about the cutting process. Figure 5 is a time plot of the acoustic emission data collected during this test.

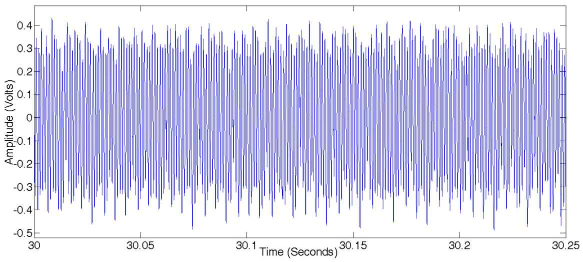


Figure 5: End Milling Acoustic Emissions Data

The data exhibits a good signal strength and correctly shows tooth passing of the milling cutter. Since this acoustic emission information does not have a flat response, the magnitude of the information is relative to the proximity of the sensor and cutting conditions. However, useful data can be identified from the frequency content of the signal. Figure 6 shows a Fourier spectrum of the acoustic signal.

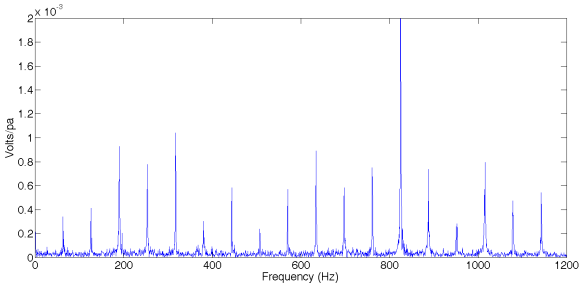


Figure 6: Acoustic Emissions Spectrum

The tooth pass frequency of 63.65 Hz is clear, however other frequencies have greater magnitude in the spectrum. As expected, this indicates that there are other sources of vibration being detected in the acoustic signal. Of specific interest is the high magnitude component at approximately 830 Hz. Upon inspecting the milling system, this frequency is intuitively attributed to vibration in the workpiece. Recalling that the workpiece is a thin plate, the work holding setup provides for overhang behind the bed vice. Although this workpiece overhang does not affect stiffness on the machining side of the vice, it contributes components to the acoustic signal. Figure 7 shows the work holding setup with respect to the cutting feed.

The value of determining workpiece frequency components is high for anticipating possible forced vibration or regenerative chatter frequencies. This is particularly the case for thin walled parts where workpiece dynamics have a significant contribution to chatter conditions.

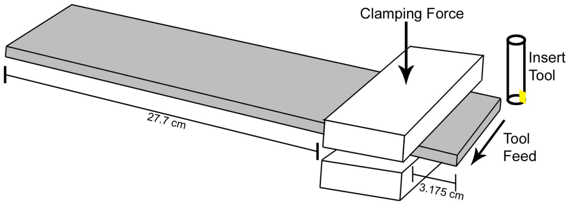


Figure 7: Work Holding Configuration

An analysis of the workpiece dynamics confirms the source of the experimentally observed 830 Hz frequency component. This is achieved by computing the first mode of vibration in the overhang to determine an estimated natural frequency. Because of the simple plate geometry, the part can be approximated as a cantilever beam. A closed form solution for vibration of a cantilever beam is described by [15]. The workpiece cross section has a width of 0.1524 m (6”) with a thickness of 0.003175 m (1/8”) and an overhang of 0.2770 m (10.9”) Assuming an elastic modulus of 200 GPa and density of ~7000 kg/m^3, the modes of the beam can be computed according to:

$$\omega_n = \alpha_n^{\,2} \sqrt{\frac{EI}{mL^4}} \qquad (1)$$

where $\alpha_n = 1.875$ for the first mode, L is the overhang length, m is the mass of the beam, E is the elastic modulus, and I is the moment of inertia. The computed natural frequency for the overhang was 853 Hz. This value agrees with the experimental observation and indicates that the acoustic signal was capable of successfully detecting workpiece modes excited by the milling process.

Acoustic Background Noise

Since acoustic emissions is used to demonstrate this system, an analysis of non-cutting data was conducted. As anticipated, it is observed that the motor and spindle vibrations are contributing significant energy to the signal. Although this is unavoidable when using acoustic emission data, this result agrees with traditional wired acoustic emissions sensor systems. Figure 8 shows the transition between non-cutting and cutting data.

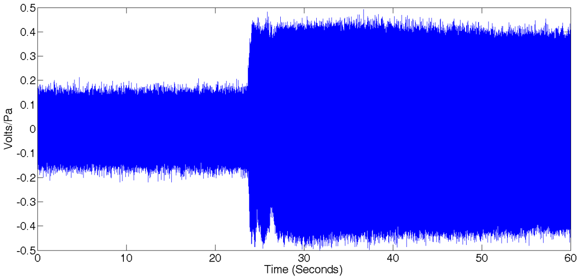
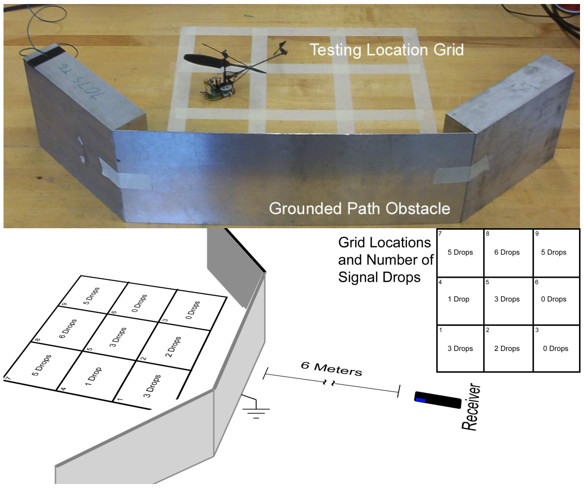


Figure 8: Background Noise vs Cutting Signal

The weakness of acoustic emission data is the high level of background noise present in the cutting signal. However, acoustic emission has high convenience for noninvasive acquisition and for demonstrating the feasibility of the system proposed in this work. Concurrent work investigates tool embedded sensor systems that are immune to ambient noise [5,6].

AVOIDING RADIO PATH INTERFERENCE

A common challenge for wireless communications in a shop floor environment is changing path interference between transmitter and receiver [7]. Consequently, the ability to remotely reposition a sensor in response to this noise is desirable. Therefore, an experiment was designed to fabricate a poor radio path condition between the transmitter and control location. Ambient noise was recorded in a quiet room and no sound was introduced during the tests. A grid was established to define nine transmission points behind the obstacle. Ambient noise was recorded from each location on the grid to determine the locations for maximal signal integrity. The transmitter is remotely repositioned to an alternate location on the grid to observe the change in signal integrity with position. Figure 9 details the path interference setup.



Grid Locations and Number of Signal Drops

7 5 Drops	8 6 Drops	9 5 Drops
4 1 Drop	5 3 Drops	6 0 Drops
1 3 Drops	2 2 Drops	3 0 Drops

Figure 9: Path Interference Setup

Data integrity is measured by counting the number of signal artifacts present during a ten second recording period. The data artifacts are attributed to dropped signal since no sources of electromagnetic noise are present during the tests. To make a quantitative comparison between tests, an artifact is counted if it exceeds four times the mean ambient noise floor. Although this metric is not robust for changing noise environments, it is sufficient to compare the effect of transmitter position when all other variables are held constant. Figure 10 is a time plot of signal transmission for grid position five. Three drops are observed at grid position five.

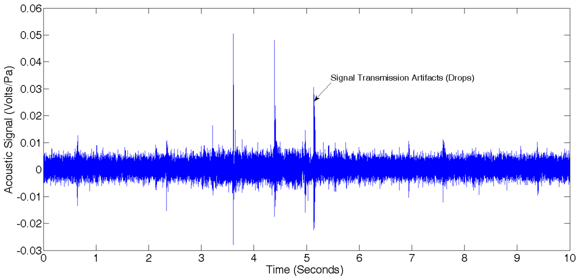


Figure 10 Artifacts due to position

To demonstrate that the number of observed signal artifacts changes with respect to position, the transmitter is relocated to all nine of the positions on the grid. It is found that positions three and six provide the best integrity with zero artifacts present during the test. By relocating the transmitter, it is shown that different levels of interference are achieved and a desirable location can be found through remotely repositioning the transmitter.

CONCLUSION AND FUTURE WORK

This work has demonstrated the feasibility of a low cost remote robot for deploying wireless sensors in a manufacturing environment. The sensor robot was capable of flying from a control location, landing within the machining envelope of an end mill, and streaming acoustic emission data to a PC through Bluetooth wireless. Useful data about the workpiece dynamics were observed from the acoustic signal and were used to explain workpiece vibration behavior during cutting. Moreover, the robot was useful for repositioning the transmitter in response to radio path interference.

Since this work has shown feasibility, there are significant opportunities to develop the concept of low cost remote monitoring robots. There are two directions of research that will evolve from this work. The first is developing a refined control interface to allow the robot platform more precise maneuverability. The components used in this work require a period of user training to develop sufficient skills to successfully control the unit. The second goal is to configure the system for full automation and guidance, eliminating manual control. Particularly, the system may be configured for RFID positioning.

A remote condition monitoring robot is potentially useful in dangerous environments, for low cost sensor deployment, and to reposition a sensor in the presence of interference. For this reason, this work is an exciting first step towards a more flexible wireless sensor solution for manufacturing processes.

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