Condition Monitoring of AMBs on the IoT

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***Abstract*—The Internet of Things (IoT) is the interconnection of physical devices enabling them to send and receive data over the internet. Using the IoT enables connected devices to acquire new capabilities. IoT technology has rapidly increased over the last decade and is being applied to industrial devices. AMBs are naturally apt to the IoT due to their inherent sensors and actuators. This study develops a method for the condition monitoring of AMB systems online using off-the-shelf IoT technology and custom software. In this study, a MBC500 AMB test rig is outfitted with a Raspberry Pi single board computer. The Raspberry Pi monitors the AMB's position sensors and current sensors via an ADS 1115 analog-to-digital converter. This setup allows users to remotely access the system and monitor its condition. Several typical rotordynamic malfunctions are imposed on the experimental test rig and diagnosed remotely, demonstrating the efficacy of the technique. The malfunctions include static loading and static and dynamic unbalance.**

I. INTRODUCTION

Active Magnetic Bearings (AMBs) are industrial devices with mechanical, electrical, and electronic components [1]. They are designed, built, and implemented by engineers and technicians with expert knowledge. Once commissioned on-site, the AMB can be used by the end user with relatively little training [2]. However, the end user may not be able to effectively troubleshoot complications with the AMB system which may arise after the commissioning process because they are not trained to recognize or diagnose them. In such cases, a field service technician from the AMB original equipment manufacturer (OEM) must go on-site to perform service. This results in down time for the system supported by the AMB and increased expense to the customer. A solution is to make AMBs part of the Internet of Things (IoT). This would allow for increased productivity and decreased costs.

The exact definition and scope of the IoT is still being developed. However, the IoT basically enables the interconnection of physical devices allowing them to send and receive data over the internet. This enables value creation beyond the mere sum of the "thing-based function" and "IT-based service" [3]. By putting AMBs on the IoT, a remote user such as an OEM technician off-site could access the AMB and diagnose malfunctions without the need for on-site examination. Therefore, the OEM technician can recommend corrective action immediately or even preemptively to reduce or eliminate equipment down time.

Early cases of what would become known as IoT were in the area of radio-frequency identification (RFID) tags such as [4] and others. Since then, there has been much development because of the significant impact on people's everyday lives [5]. There are several instances of industry beginning to take advantage of IoT technology [6]. More recently, IoT has been applied towards structural health monitoring [7]. For example, IoT has been used for monitoring the position in the continuous casting of steel [8]. Also, IoT was used for the monitoring of vibrations in electric motors [9]. This suggests the potential of AMBs coupled with the IoT.

Still, there has been little work in the area of IoT tools used for condition monitoring for AMBs. Although, some IoT component technologies have been developed for some different applications. Tucker and Harvey used remote client/server approach for AMB controller tuning [10]. A LAN was used for communication with a real-time control platform for AMBs for performing experiments at a safe distance in [11]. Whereas, a TCP/IP was used for remote inspection and diagnostics in [12]. Jayawant and his colleagues developed an automated commissioning program capable of remote commissioning AMBs via TCP/IP and a SOAP interface [13-15].

In the current work, an AMB test rig is augmented with an off-the-shelf IoT gateway. The device is programmed to read the AMB's sensors. A remote user is then able to log-in to the device to observe the sensor signals. The usefulness of the developed system for condition monitoring of AMBs is demonstrated by running the test rig under different conditions and presenting the remote user interface illustrating how the condition of the system is evaluated.

The next section explains the concept of using the IoT for condition monitoring of AMBs. Next, the experimental system used to demonstrate the proposed method is detailed. Then, the experimental results are presented. The practical issue of sampling time when utilizing the IoT gateway device is discussed. Finally, the paper is ended with some concluding remarks.

II. AMB CONDITION MONITORING ON THE IOT

An AMB uses a magnetic field to support a rotating shaft. The magnetic field is generated with an array of electromagnets around the rotor. The electromagnetic force induced on the ferromagnetic rotor is inherently unstable. The position of the shaft is measured in real time by a noncontact position sensor. The position data is used by a controller to calculate how much current is needed in the electromagnetic coils to maintain a stable levitation. Therefore, an AMB, by its nature, includes sensors and actuators. It is suitable for condition monitoring for traditional rotordynamic faults [16]. And, it is also highly apt to be extended to the IoT.

By accessing the AMBs' sensor signals, a remote service technician can monitor the condition of the AMB system. The overall concept for the proposed method of AMB condition monitoring via the IoT is illustrated in Fig. 1. The figure shows the AMB configuration with differential control of opposing electromagnetic coils by adding or removing current from a positive bias current. Therefore, the coil currents will be nonnegative at all times. Also, two opposing gap sensors are wired differentially to effectively control the geometric center of the rotor.

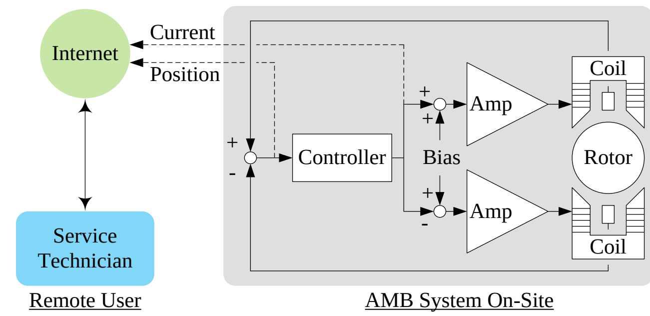

Figure 1. Condition monitoring of AMB system via the IoT Concept.

In the proposed scheme, the rotor position and the coil current, available from the AMB, is accessed for the IoT. Therefore, a service technician can log in remotely to the gateway and troubleshoot the AMB system. The remote technician is granted the ability to diagnose a variety of equipment malfunctions. The technician may be able to recommend corrective or even preventative action to the AMB end users without the need for an on-site service visit.

For example, if the rotor position is low and/or the coil current is high, it may indicate shaft overloading. The technician can recommend checking the application or spec out a larger AMB. Another scenario could involve the remote technician observing an overly large orbit indicating large unbalance. The technician can recommend rotor balancing before continued operation.

III. EXPERIMENTAL SYSTEM

The experimental system used to develop the proposed IoT condition monitoring solution consists of a stand along AMB test rig coupled with an IoT gateway and other required hardware. The AMB test rig is model MBC500 by LaunchPoint Technologies Inc. which has sensor signals readily available via a front breakout panel. The IoT gateway selected is the Raspberry Pi 3 Model B single board computer. The experimental system is shown in Fig. 2.

Additional hardware is required for interfacing the Raspberry Pi with the analog signals of the AMB rig. Specifically, an analog-to-digital converter (ADC) board and amplifiers are used to condition the sensor signals to the appropriate range.

The following subsections detail the AMB test rig configuration, electronic hardware for IoT implementation, and corresponding software.

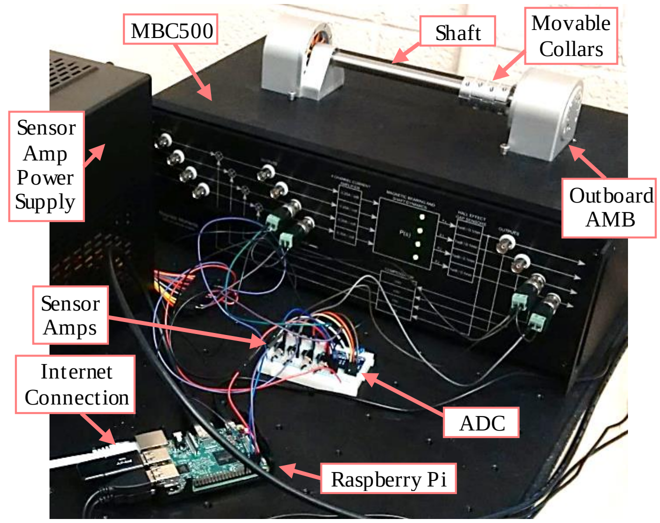

Figure 2. Experimental AMB test rig with attached Raspberry Pi single board computer, ADC, and conditioning circuitry.

A. AMB Test Rig

The MBC500 AMB test rig consists of a single shaft supported by two radial AMBs at either end. Shaft position is monitored by Hall effect sensors to the immediate outside of the magnetic coils. The shaft is stainless steel and 12.5 mm in diameter. Rotation is driven by an air turbine by the inboard AMB.

Movable collars are added to the shaft to create reconfigurable weight and unbalance loads. The collars are approximately 10.5 mm wide and 28 mm in diameter. Two collars are used for the present test, one aluminum and one stainless steel. The aluminum collar is 15 g and the stainless steel collar is 36 g. The position sensors are 2.8 mm from the ends of the shaft. The locations of the AMBs and the collars on the shaft are shown in Fig 3.

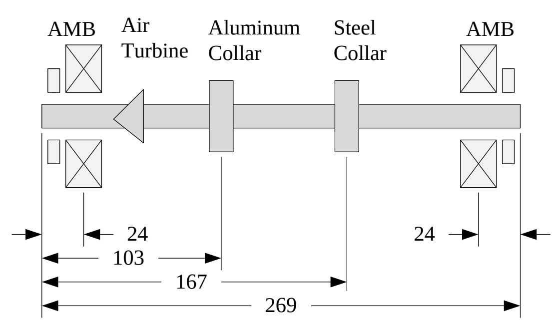

Figure 3. Rotor configuration. Dimensions in mm.

The AMBs are eight pole and wired differentially in the vertical and horizontal axes. Each AMB axis has a bias current of 0.5 A and a nominal gap of 400 µm. The AMB force constant based on coil geometry is 2.8×10^{-7} N-m^2/A^2. The current amplifier bandwidth is approximately 720 Hz. The AMB controller built into the MBC500 is local lead-lag type. The built in controller is used for the IoT condition monitoring study when the shaft collars are moved.

B. *Hardware Added for IoT*

The IoT gateway selected is the Raspberry Pi 3 B. The Raspberry Pi is a single board computer with a 1.2 GHz Broadcom BCM2837 Quad-Core CPU and 1 GB of RAM. It runs the Raspbian operating system which is Debian based. It serves as an economical off-the-shelf IoT gateway.

The hardware interface of the Raspberry Pi is general purpose input-output (GPIO) digital pins. To read the analog signals from the AMBs, an ADC must be added. For the current study, a Texas Instruments ADS1115 4-channel 16-bit ADC is utilized. Communication between the Raspberry Pi and ADC is implemented via standard I^2C digital communication protocol requiring two wires, one for data transfer and one for timing trigger.

The basic scheme for experimental implementation of AMB condition monitoring via IoT is shown in Fig. 4.

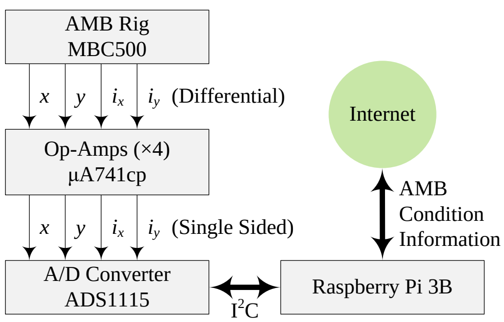

Figure 4. Experimental IoT Scheme.

The ADC input range is nondifferential, effectively 0 to 5 v. The AMB sensors' operation range is within ±4 v. The sensor signals are scaled and offset by an array of four summing amplifiers. Texas Instruments µA741cp general purpose operational amplifiers are used. The amplifiers are wired as shown in Fig. 5 to achieve the required signal voltage range where V_I is the input sensor signal from the AMB and V_O is the output signal sent to the ADC.

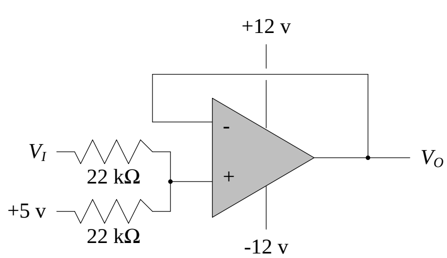

Figure 5. Wiring diagram for summing amplifiers used to offset differential sensor signals to non-differential voltage range.

A standard PC power supply provides an economical source of +12 v and -12 v as well as the 5 v needed to raise to sensor signals. The resistors are balanced to half the overall sensor signal. The exact value of the resistors is selected through trial and error for an acceptable impedance match.

One AMB of the fully levitated system is monitored to demonstrate the developed IoT condition monitoring system. The sensor signals monitored are shaft position in the horizontal and vertical directions, *x* and *y*, respectively, and the corresponding axis coil currents, i_x and i_y, respectively. The software loaded on the Raspberry Pi uses this data to give insight to the operating conditions of the outboard AMB.

C. *IoT Software*

The IoT condition monitoring software is written to collect the output signals of the ADC unit and display a visual representation of data. This includes rotor position and coil current. The ADC samples each signal and converts from voltage to bits. The bit readout is communicated to the Raspberry Pi via I^2C protocol. The bits are then scaled to recover the real-world signal values. This involves applying an offset and sensitivity to the vectors of collected data. The offset constants for the positions are obtained by averaging the position vectors during healthy levitation. These values are subtracted from all the corresponding values in each corresponding vector. The sensitivity, found by comparing a known physical travel to the change in bits, is multiplied into each value in the respective vector. This yields the calibrated position. A similar process is done for the current, but with the addition of offset to accurately represent the bias current applied.

The vectors of position readings and current readings are then plotted to display orbits (*x* vs *y*) and position *y* with time and frequency. The frequency plot is generated by taking the Fast Fourier Transform (FFT) via the NumPy library of a reconstructed position vector as follows. The original sampled position vector has inconsistent time steps due to the nature of the Raspbian operating system. Since the same processor running the operating system is also running the monitoring program, the loop running the code may be suspended to maintain the operating system's processes. The exact sampling rate is discussed in a later section. To perform the FFT, which requires a consistent sampling rate, the original data vector is resampled via linear interpolation. It is selected to use a resampled vector with 512 elements from the original approximately 400 over 5 s time history. This number of virtual samples is selected to optimize the FFT algorithm while being similar to the actual number of data taken to maintain fidelity.

The plotting of position and current vs time and in the frequency domain gives insight into the AMB system's operating condition. The software places these figures as well as the average value of each of the considered parameters after each instance into a graphical user interface (GUI). From the Raspberry Pi, a remote monitoring technician can observe the motions of the shaft within the bearing and alert on-site operating technicians of a possible malfunction.

To connect remotely to the IoT AMB, Secure Shell (SSH) cryptographic network protocol is enabled to allow connection from an outside source. The Raspberry Pi hosts a server using the program VNC Server and the technician uses VNC Viewer (client), both by RealVNC Ltd., to facilitate the connection with RFB protocol. This allows the remote user to activate the IoT program and observe the operation of the bearing through the GUI.

For the current study, the program performs data collection and display results for a set time interval, 5 s. Future editions may allow the program to display latency and constantly updating values and automatically replot figures.

IV. EXPERIMENTAL DEMONSTRATION

Six trials are conducted to demonstrate the condition monitoring capabilities of the developed AMB IoT system. For each trial the shaft collars are adjusted to create varying load conditions. Two trials are conducted with the shaft levitated but not rotating. Two trials are conducted with the shaft rotating. Two trials are conducted with the shaft rotating with added unbalance. For each case, the GUI used by the remote service technician is presented to illustrate how the condition of the AMB system is monitored.

A. Nonrotating Tests

Figures 6 and 7 show the GUI a remote service technician would see when executing the IoT AMB monitoring software. The top of the GUI is a header which displays basic information. The period over which data is collected is displayed, in this case 5 s. There is a blank expansion field for latency to be displayed by a later version of the software. Average values for position and current in the vertical and horizontal AMB axes are also displayed.

The two leftmost plots are orbits, plotting data from vertical vs horizontal AMB axes. The first plot displays rotor position and the second displays top coil current calculated from the recorded control current. The default scale for the position orbit is nominal AMB airgap of ±200 µm. Therefore, the technician can easily determine if the rotor is near the limit of safe operation. The default scale for the current orbit is 0-1 A. A non-levitated rotor would sit at (0, -400) µm in the position orbit and (0,0) A in the current orbit.

The center right plot displays the time response of the rotor vertical position over the entire 5 s time history. The rightmost plot displays the corresponding frequency spectrum found with an FFT of the resampled position data

Figure 6 is for the nonrotating shaft without added collars.

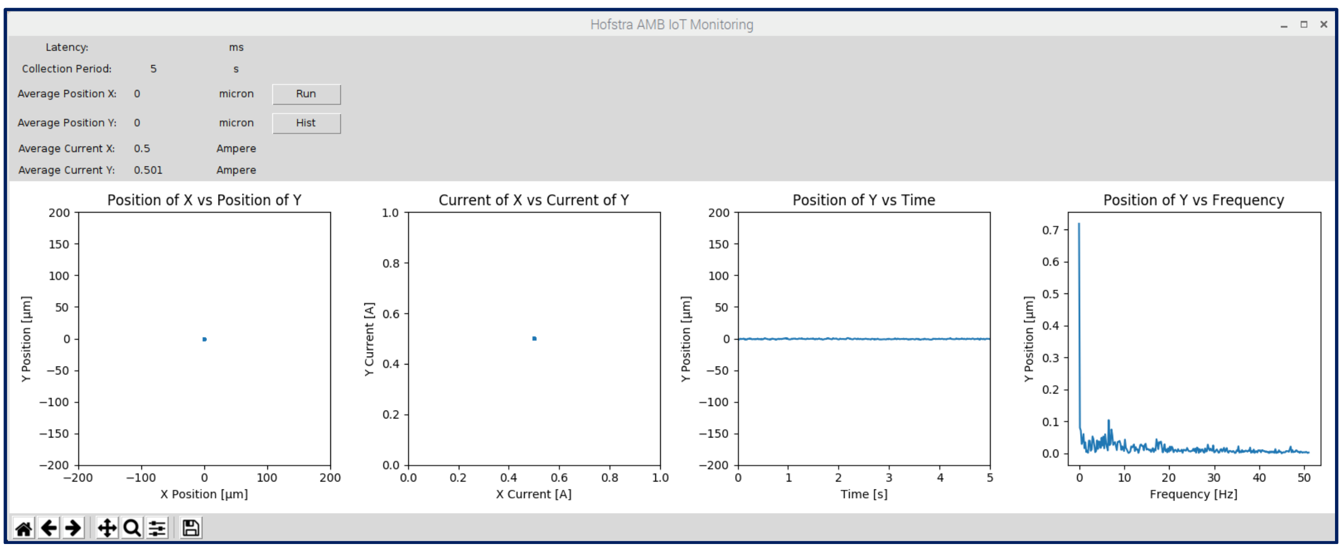

Figure 6. AMB IoT Condition monitoring GUI display for non-rotating bare shaft.

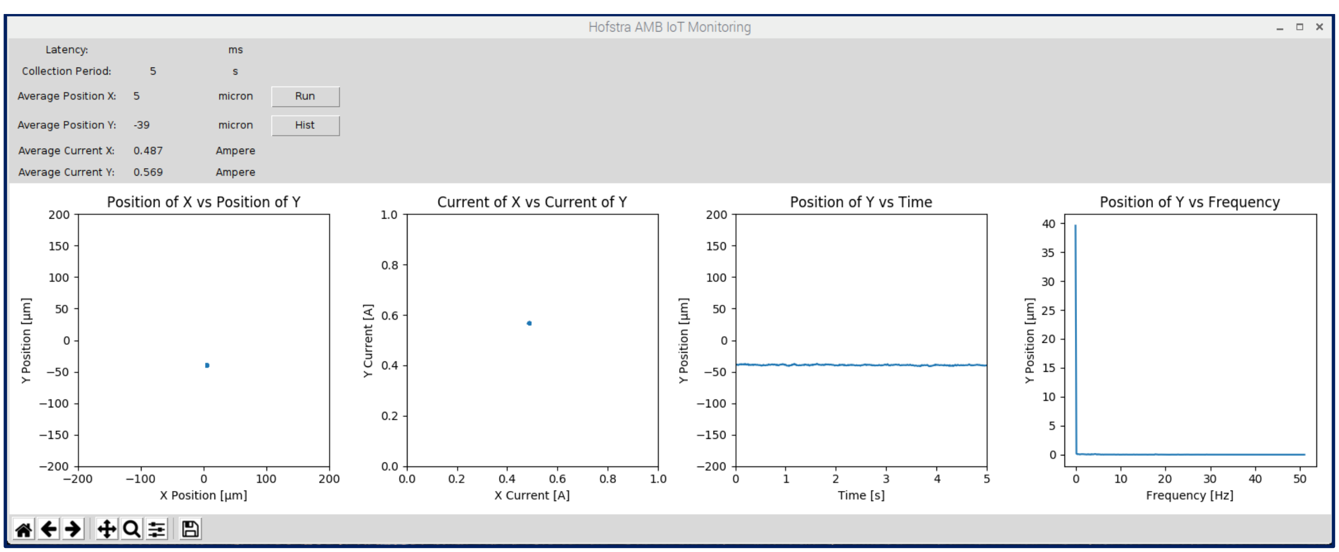

Figure 7. AMB IoT Condition monitoring GUI display for non-rotating shaft with two collars.

The shaft levitates steadily near (0,0) μm, the center of the AMB. The coil current is near the bias current, 0.5 A. The calibration of the IoT condition monitoring system can differ from that of the AMB controller.

The frequency spectrum shows only a zero Hz component for static offset. Note that the AMB controller has no integral action like in a common PID controller. Figure 7 is for the nonrotating shaft with the two added collars. The remote service technician can divine the static loading condition of the levitated rotor by noting the lower levitated position and increased static current. In the event that the static deflection was too low or the static current was too high, the remote service technician can diagnose rotor over loading and recommend proper corrective action to on-site personnel without the need for an in-person inspection.

B. *Balanced Rotating Tests*

The rotor is rotated at 1200 RPM with and without the shaft collars. Figure 8 is the IoT condition monitoring GUI for the case without the collars and Fig. 9 is that for the case with the collars. The remote service technician can observe the orbit of the rotor inside the AMB air gap cause by the rotation. For both cases, the orbit is consistent and stable. The added weight of the shaft collars causes static deflection downward and corresponding increase of current (as with the nonrotating cases). The increase of gravity preloading also causes a slight bearing stiffness anisotropy which leads to elongation of the orbit in the vertical direction and is observable by the remote service technician.

The rotation condition of the rotor is further observable in the time plot which displays a consistent harmonic wave. The frequency spectrum has a peak at approximately 20 Hz indicating the running speed. The case with the shaft collars has a slightly higher peak at the running speed due to residual imbalance of the collars. The remote service technician can inspect the frequency spectrum for other frequency components. For example, rotation off of the bearing centerline leads to the appearance of a 2× rotation component in Fig. 9 at 40 Hz.

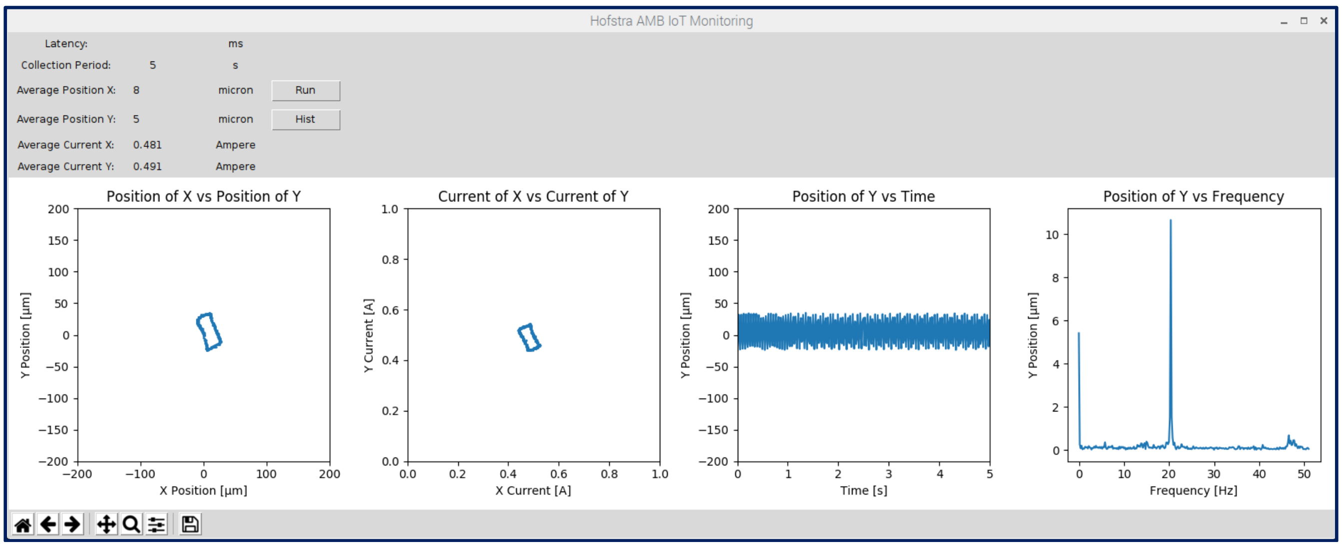

Figure 8. AMB IoT Condition monitoring GUI display for rotating bare shaft.

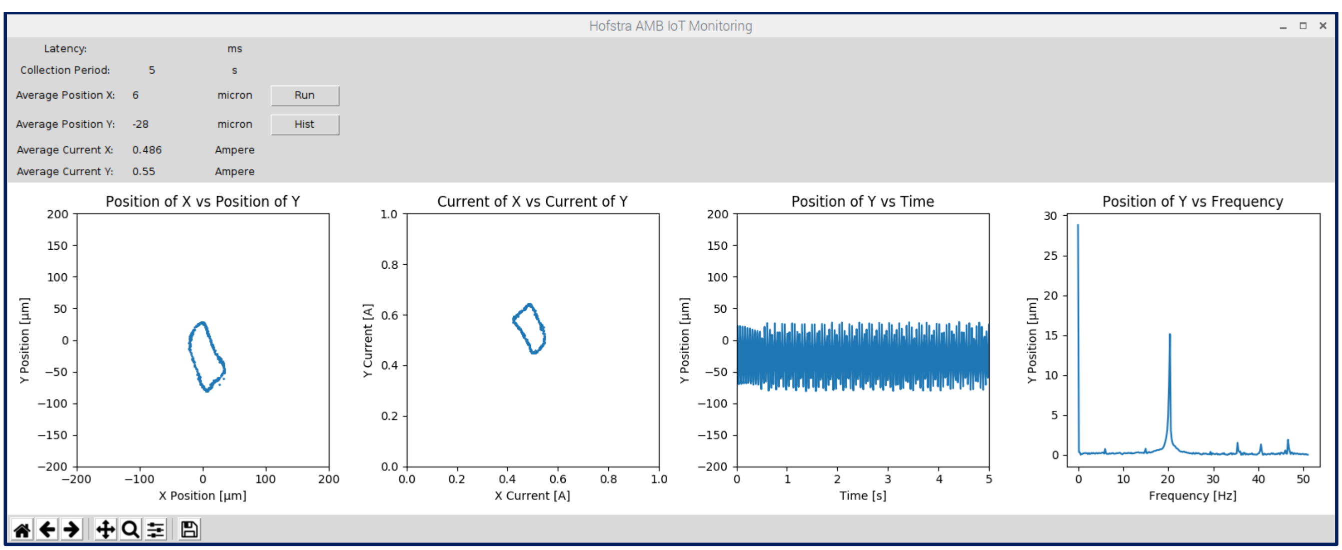

Figure 9. AMB IoT Condition monitoring GUI display for rotating shaft with two balanced collars.

C. *Unbalanced Rotating Tests*

To induce a rotordynamic malfunction, unbalance masses are added to each shaft collar in the form of a machine screw with exposed head. The resulting unbalance is approximately 6.5 g-mm per collar. Two unbalance tests are conducted. The first has both unbalance screws in the same direction on the rotor to create a static unbalance. The second has the unbalance screws in the opposite directions on the rotor with the goal of creating a dynamic unbalance. Again, the shaft is rotated at 1200 RPM.

Figure 10 presents the IoT condition monitoring GUI for the static unbalance test and Fig. 11 presents that for the dynamic unbalance test. Observing the GUI of Fig 10, a remote service technician can diagnose the rotor unbalance from the slightly increased level of vibrations. This is seen in the orbit size, vibration amplitude in time, and 1X frequency peak.

The result of the dynamic unbalance test is the unbalance increases in the aluminum (inboard) collar but the added mass of the stainless steel (outboard) collar countered its own residual unbalance. Therefore, the remote service technician would observe a healthier orbit size albeit lower in the bearing gap. The ability to remotely access these data enables the remote service technician to recommend rotor balancing to the end user.

V. SAMPLING RATE PERFORMANCE

A limitation of the developed IoT condition monitoring solution is the inconsistent sampling rate stemming from the operating system of the IoT gateway device. This is different from, for example, a dedicated microcontroller which has no operating system and no related background activities. The developed IoT program executed in Raspbian achieves a typical sampling rate of 100 Hz. However, it suffers from periodic delays encountered as the operating system performs background processes. These are the functions maintaining the operating system and functionality of peripherals and other programs run by the remote user. Figure 12 shows the time stepping history of a characteristic 5 s condition monitoring run.

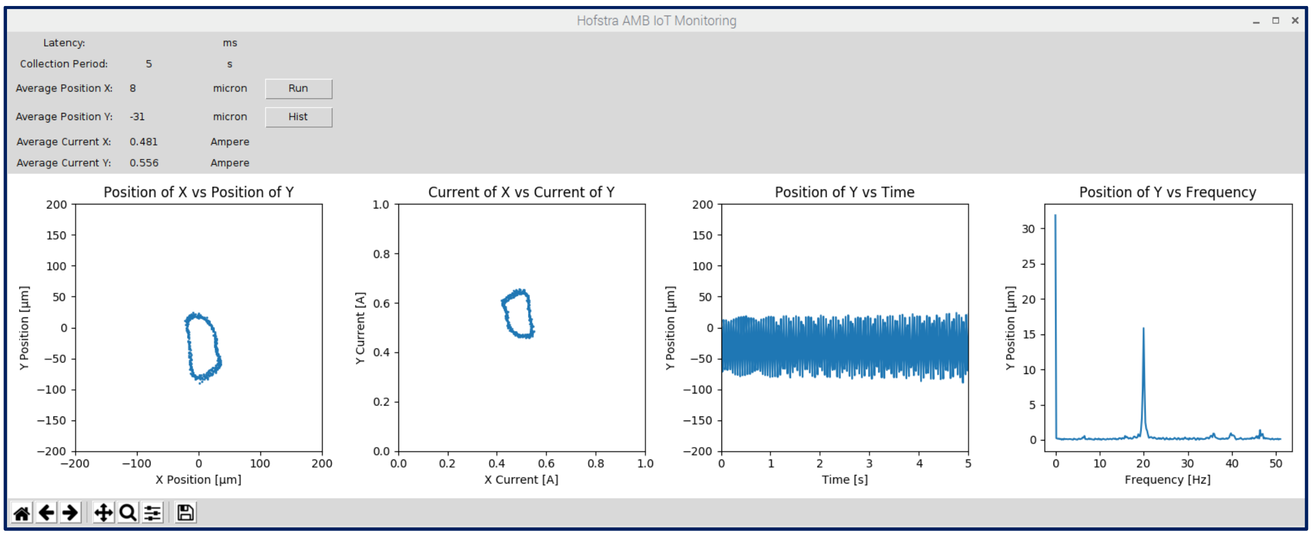

Figure 10. AMB IoT Condition monitoring GUI display for rotating shaft with two collars and static unbalance.

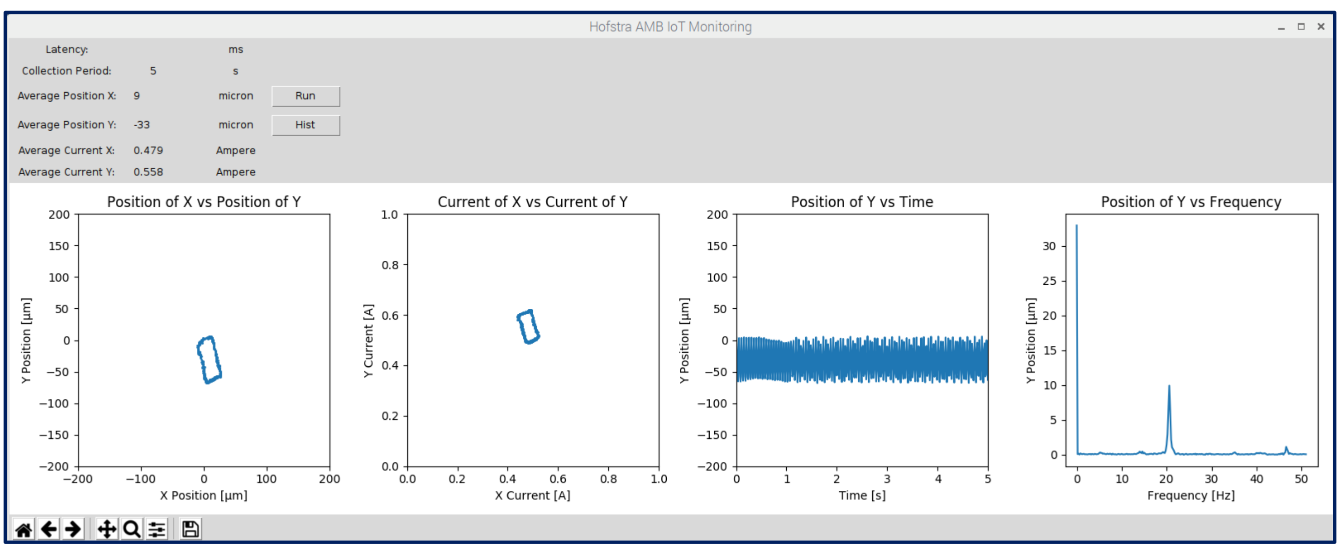

Figure 11. AMB IoT Condition monitoring GUI display for rotating shaft with two collars and dynamic unbalance

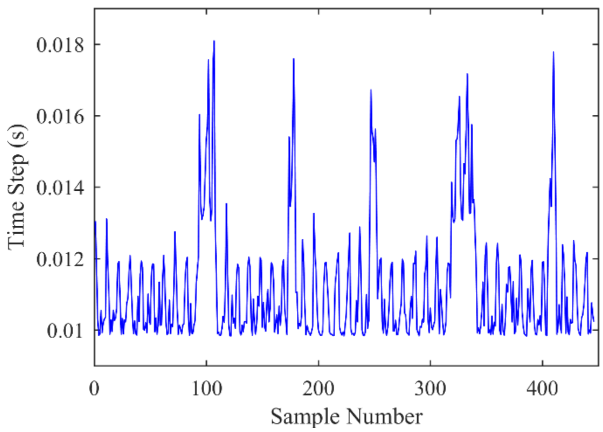

Figure 12. Characteristic sampling time history for 5 s of IoT data.

The nominal sampling time of 0.01 s is seen as the baseline level in the figure. Frequently, the time is delayed to around 0.012 s. Also, the data collection is pseudo periodically delayed even further for several time steps about every 1 s. This leads to a time step as high as 0.018 s. A histogram of the sampling time for this 5 s run is shown in Fig. 13.

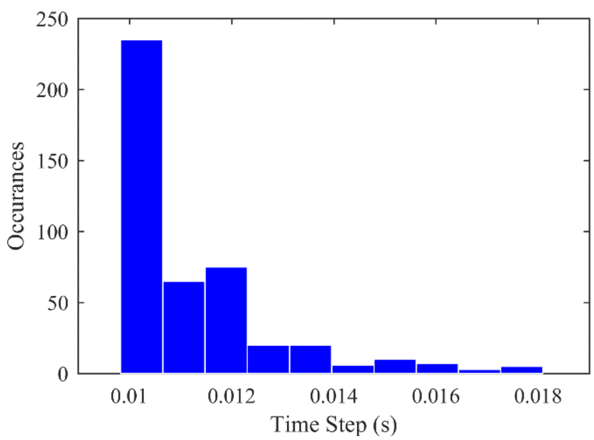

Figure 13. Histogram of characteristic sampling time for 5 s of IoT data.

The histogram confirms that the nominal sampling time is dominant but is interrupted by occasional delays. This limitation is overcome for the current study by visual inspection of orbits (which are not highly time dependent) and resampling to achieve practical frequency spectrum. However, this issue is important in further development of IoT for AMBs, that is execution of active control online. A possible solution may be implementation of a real-time operating system. Another solution is implementation of a programmable real-time unit on a single board computer.

VI. CONCLUSIONS

This paper addresses the problem of remote condition monitoring of AMBs. A solution was proposed to use off-the-shelf IoT hardware and custom software to tie into an AMB's position and current signals. This allows for an OEM technician to observe them remotely. The proposed strategy is demonstrated on an AMB test rig. A raspberry Pi gateway and VNC Server software are used to implement IoT connection. Static loading, and static and dynamic unbalance were imposed on the experimental rotor. The condition of the AMB system were successfully monitored remotely for each case.

Therefore, it is found that off-the-shelf IoT hardware and custom software are effective at tying in AMBs to the IoT for condition monitoring. AMB OEMs can implement similar methods to remotely monitor their products which are operating on-site for their clients, the end users. This ability will alleviate the need for on-site service calls and prevent AMB down time.

There are several promising directions of future work for further development of AMBs and IoT. First, cybersecurity should be considered. Also, a mobile app can be developed using the same basic scheme such that AMB users can check on the condition of the system from arbitrary locations. More involved is the improvement of the IoT scheme to be real-time. Two possible solutions are a real-time operating system for the IoT gateway and using a real-time programmable unit. Real-time execution will lead to the next stage of development, a cyber physical system. That is, the feedback control for the AMB will be done through the IoT making a system in which the real-world dynamics of the system are dependent on the cyberworld. Then, an OEM service technician will not only be able to monitor the condition of an AMB system and diagnosis problems, but also may be able to fix problems by changing the control law.

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