We present a flexible wireless monitoring system for condition-based maintenance and diagnostics tailored for dynamic and complex experimental setups encountered in modern research laboratories. Our platform leverages an Internet-of-Things approach to monitor a wide range of physical parameters via customized sensor modules that broadcast to a networked computer. We give a specific demonstration for a so-called ultracold atom machine, which is the workhorse of many emerging quantum technologies and marries a broad spectrum of equipment and instrumentation into its setup. We supply prescriptions for the implementations of a range of sensor modules and describe the services we use to store, process, and visualize the data collected.

1. Introduction

The advent of laser cooling opened up a way to produce trapped atomic gases at temperatures only a few microkelvin above absolute zero, initiating the field of ultracold atomic physics [1]. Augmenting laser cooling with evaporative cooling, a push was made to the nanokelvin domain where Bose-Einstein condensates and degenerate Fermi gases were attained. These systems have remained at the cutting-edge of research because they offer a pristine environment to explore fundamental quantum phenomena, and the experimental platforms used in their production can accurately be referred to as ‘ultracold atom machines’ [2, 3]. Such machines are extremely complex, hybridising many different technologies from optical, microwave, vacuum, electronic, and mechanical engineering. They typically incorporate both commercially available equipment and custom-built hardware, patching a variety of systems together to get a functional ultracold atom machine and an optimised process sequence. The end product of running a process cycle – a small gas cloud a few billionths of a degree above absolute zero temperature – is extremely sensitive to changes in the process and the environment. A reproducible result is hence strongly tied to these conditions remaining stable. Accordingly, variations in the end product may be associated with variations in specific monitored process parameters through suitable analysis. For example, Ref. [4] employed commercial data acquisition hardware to monitor 50 parameters of an ultracold atom machine and tied fluctuations in the final atom number to the temperature of a magnetic field coil.

Condition monitoring is well known in conventional processing plants, as monitoring equipment parameters allows for condition-based or predictive maintenance [5], leading to increased equipment up-time and smaller maintenance and operating costs. These benefits could also be reaped in a research laboratory setting. Towards this end, we present an approach based on ‘Internet-of-Things’ (IoT) technologies and ideas – an approach which is formed around having large numbers of devices (‘things’) connected to the Internet [6], and has grown in popularity with the availability and declining cost of hardware with networking capability. IoT ideas are also finding use in conventional processing plants [7], home automation [8], wearable technology, and healthcare [9].

Here we report on a flexible condition-monitoring system of wireless sensor modules and services for collection and analysis as shown in Fig. 1. Our system is capable of interfacing with a variety of sensors and with commercial instruments. We demonstrate the features of this system and provide examples of its usage. We also supply detailed documentation and code to build this system [10].
2. Sensor module

Our sensor modules are based on the ESP8266 by Espressif Systems which is a self-contained System-on-Chip with built-in WiFi. This module also contains a 10-bit analog-to-digital converter (ADC), digital serial capabilities (including UART, I2C, SDIO, SPI), and 17 general-purpose input-output (GPIO) pins. We specifically use the NodeMCU V1.0 development board [11], which adds a USB serial interface for convenient programming and a supply voltage regulator. It also extends the range of the ADC from 1 V to 3.2 V via a voltage divider.

Each of our sensor modules is programmed with firmware according to the application and containing drivers for the attached sensors. Our code [10] provides a ready-to-use framework where firmware is uploaded to the NodeMCU board via its USB connection (we use the PlatformIO tools [12] for this purpose). Once deployed, the device can be reprogrammed via WiFi from a web-browser. Our code library contains detailed information and instructions on configuring and deploying the modules. Essentially, the steps to be followed can be summarized as:

- Set up the data collection services on a networked computer in the laboratory (only needs to be done once).
- Connect sensors to a NodeMCU board.
- Specify the connected sensors in the firmware.
- Build firmware on computer (via PlatformIO) and upload it to the NodeMCU via USB (the NodeMCU will now broadcast a WiFi network).
- Deploy sensor module in lab.
- Connect to WiFi broadcast by the NodeMCU and configure the sensor module to connect to WiFi in the lab and publish measurements to the data collection server.

Below we present some of the sensors that we have deployed in our experiment, for which we provide code.

2.1. Temperature sensor

For contact temperature measurement we primarily use the DS18B20 from Maxim Integrated, which we fit into various places in our machine. Each sensor has an on-board digital interface, and is capable of reporting the temperature to a resolution as good as 62.5 mK [13]. We find the TO-92 package (small “transistor” shape) of the DS18B20 to be a convenient size to locate throughout our apparatus. We also employ some which are enclosed in a water-proof housing.

To construct a sensor module from the DS18B20, one connects it to an ESP8266 as shown in Fig. 2, then configures the firmware specifying a DS18B20 is connected, and a handle to identify the measurement. Multiple DS18B20 devices can be connected to the same GPIO pin on the ESP8266 and read out separately as they have unique IDs.

For an even smaller sensor head or to measure temperatures extending above 125 °C, we use K-type thermocouples, with the MCP9600 16 bit thermocouple-to-digital converter from Microchip. This device features all required signal conditioning,
support for multiple types of thermocouples, and built-in compensation for the cold junction formed by connecting the thermocouple to the converter.

2.2. Atmospheric Sensors

To measure atmospheric signals of interest, such as ambient temperature and humidity, we use the AM2302 from Aosong Electronics – a small digital sensor which can measure the ambient temperature and relative humidity. Another sensor we use for this purpose is the BME280 from Bosch Sensortec, which additionally measures the atmospheric pressure.

From these signals one can, for example, detect changes in the lab environmental control or the function of a positive pressure environment. In particular, we have found it useful to monitor the outside temperature with an atmospheric sensor module mounted on the side of the building to examine the impact of temperature on our cooling water system.

2.3. Analog Voltage Measurements

Virtually any physical quantity we want to measure can be converted to an analog voltage by some electrical transducer, for example; currents (using a sense resistor, or hall-effect sensor), resistance (using a bridge circuit), temperatures (using a thermistor), forces/pressures (with a strain gauge), and magnetic fields (with hall-effect sensors). Furthermore, many industrial sensors produce an analog signal of 4–20 mA, and many research instruments provide a voltage output to monitor signals of interest. The variety of applications for monitoring analog signals makes this an important feature of our framework. Figure 3 shows two configurations for this task.

2.3.1. Internal ADC

The ESP8266 features an onboard ADC with a native 0 V to 1 V range, which on the NodeMCU boards has been extended to a 0 V to 3.2 V range with a 220:100 kΩ resistive voltage divider. This range can be adjusted by suitable replacement of the resistors of the NodeMCU board or by adding a resistor inline with the signal.

The onboard 10-bit ADC is referenced to the chip ground, and hence the ESP8266 must share its ground with the signal. The ground does not have to be at the earth potential, as the ESP8266 can be powered from an isolated/floating power supply or battery. This allows for making measurements in galvanic isolation from earthed equipment.

Our testing has demonstrated that the analog input pin of the ESP8266 is not tolerant of negative voltages (less than −0.3 V), or voltages exceeding 3.3 V. The input range that can be measured is only 0 V to 1 V. Note that the ESP8266 should be powered whenever it is connected to a signal source, as the input’s behaviour and tolerance changes when not powered.

The onboard ADC can be sampled at a rate of about 2 kHz, but for most of our monitoring applications, we sample at much lower rates, e.g., 1 Hz.

2.3.2. External ADC

For higher resolution measurements, we use the ADS1115 analog-digital converter from Texas Instruments, which provides higher-resolution (16 bit) conversion, on four input channels, and a programmable-gain input. This allows a maximum measurement range of ±6.144 V, though the input pins can only tolerate −0.3 V to 5.3 V when run off a 5 volt supply. Negative signals are only possible with differential measurements between two positive voltages. Similarly to the internal ADC, one can make floating measurements with care.

2.4. Magnetic field sensors

Ultracold atoms are particularly sensitive to magnetic fields. Hall-effect sensors are one way of measuring these fields and present an analog signal which can be monitored as previously described. We use a digital magnetic field sensor, the MLX90393 from Melexis. This is a 16-bit, 3-axis magnetometer capable of measuring fields of ±500 G, which we find suitable for monitoring our magnetic traps and background fields. A variety of alternative digital 3-axis magnetometers exist, but many are manufactured as digital compasses and saturate at fields of as little as 4 G.

2.5. Digital signal monitoring

Commercial instruments embedded in our ultracold atom machine often have TTL outputs, e.g. “PLL locked”, “Laser locked” or “Error”, which we track via sensor modules. Other interesting digital signals include laser interlock status, comparator outputs, or timing signals, so the monitoring system is aware of the state of a process cycle.

The 17 GPIO pins of the ESP8266 can be used to monitor the state of digital signals. The ESP8266 is a 3.3 V device, but the GPIO pins are 5 V tolerant and can accept standard 5 V TTL signals. For higher voltages, a resistor should be put in series with the signal to limit the current to less than 12 mA, preventing damage of the GPIO pins.
2.5.1. Time-sensitive Digital Signals

Our flow meters for cooling water produce pulsed signals with the pulse rate being a measure of the flow rate. The GPIO pins of the ESP8266 could be used for these tasks, but the processor in the ESP8266 needs to spend time dealing with WiFi or maintaining the connection to the data collection server. When the processor is busy it is non-trivial to make consistent timing measurements. To overcome this problem, we use an external processor (an ATMega328P from Microchip on an Arduino Nano 3 board [14]) to perform time-critical functions.

To measure the pulse rate of our flow meters we have one of these external boards programmed as a frequency counter and we read the frequency out with the ESP8266 via a digital serial connection (I2C). A similar system can be used to make pulse width measurements (e.g., monitor a laser beam shutter’s opening time to detect if it is stuck) or perform a Fourier transform on analog signals to examine the spectrum of an incoming signal.

2.6. Serial interface readout

Commercial instruments often contain a digital serial interface for remote control. These interfaces, e.g. RS232, RS485 or GPIB, generally provide the ability to query the status of the device. To connect the ESP8266 to the interface, we use commercially-available TTL-to-RS232 adapters (based on the MAX232 [15]) and home-built GPIB adapters (based on a third-party design [16]) with the ESP8266. This is to meet the physical properties of the signal protocols (e.g. the ±25 V compliance range of RS232).

GPIB, or IEEE-488 is an industry standard that has been use in test instrumentation since the 1960s for automation and control. Our system therefor opens up the possibility of retrofitting old high-end equipment with wireless monitoring capabilities.

We use a sensor module to track the status of power supplies for electromagnets. Here, data is polled from the power supplies over GPIB which is collected by a serial interface on the ESP8266 with the help of a TTL bridge compatible with GPIB as shown in Fig. 4.

3. Publishing data to server

The sensor modules connect to a message queuing service [17, 18] to which they transmit data (see Fig. 1). This service is run on a networked computer in the lab, which forms a data collection server. Data messages are sent as strings from each sensor module to the service with the value and units of each measurement. The messages are ‘published’ to different ‘topics’ on the server, which differentiates each signal being monitored. Other clients are then able to ‘subscribe’ to the ‘topics’, and receive the measurements.

When first deployed, a sensor module initially starts up its own WiFi network and awaits configuration from a web-browser (a mobile phone can be used for this purpose). This configuration specifies the SSID and password for the WiFi network to which the data collection server is connected, as well as the address of the server. Once configured, the device’s network disappears, and the module starts transmitting data.

In order for the data to be useful for analysis, we must have a way of storing it. We use the “agent” program Telegraf [19] to collect the data messages and store them in a time-series database, InfluxDB [20]. The data flow is shown in Fig. 1.

It is straightforward to send measurements to the message queuing service from sources other than our ESP8266 sensor modules, as the messages are transported in a simple string format, and the message queue interface is an open standard with many implementations available. Instruments that have USB, FireWire or network interfaces do not lend themselves easily to interfacing with the ESP8266, but using suitable drivers for these instruments connected to a computer, one can upload measurements to the message queue component of the monitoring system to take advantage of the analysis tools described in the following sections.

4. Front end / action analysis

The setup we describe uses separate tools for real-time analysis, and for interacting with historical data (i.e., data stored in the InfluxDB database). Details on the services and their configuration can be found with our code [10].

Here we explain the user-facing tools that we use.

4.1. Visualisation

To visualise the data stored in the InfluxDB database we use Grafana [21] which offers “drag and drop” construction of monitoring dashboards and database queries. Grafana is accessed via a web-browser, allowing users to view the data remotely and from multiple computers simultaneously. It can also be made publicly and globally accessible via the internet, as we have done [22].

Grafana provides a number of ways of visualising data as ‘panels’ on a dashboard. Fig. 5 shows a simple example using graph and gauge panels. Grafana includes other panel types including bar gauges, tables, and heat maps. With these tools, one
can create “control panel” type displays, or even “digital checklists”, where the operating state is indicated by colour, quickly highlighting anything that is not operating normally. Grafana supports multiple dashboards, and one can set the display to automatically change through them to get a live overview of the system. Grafana also offers a simple way for users to query and export data, avoiding having to interface with the database directly.

4.2. Real-time Analysis

Our real-time analysis operates on data received from the message queue server directly, so detects if there is a fault with the experiment as data comes in. We may either wish to avoid wasting time collecting faulty experimental data, or we may try to act to correct the failure or minimise damage caused by the failure. The last point is the realm of safety devices (e.g. thermal fuses), and while it is not recommended to displace hardware interlocks and failsafes, real-time analysis opens up interesting ways to augment these. An advantage of using the monitoring system to perform these features is the large amount of data available. For example, one may use data from multiple sensors simultaneously, e.g. differential flow rates between source and return lines can detect a leak.

For real-time analysis we use NodeRED [23] which runs on the data collection server and provides a web-based graphical and JavaScript programming environment for reacting to messages from the message queueing server.

We use NodeRED to perform some preventative actions, such as shutting off our coolant pump if the system detects a leak or if the coolant tank is low. We can also disable the power supplies if the electromagnets being cooled get too warm or if the flow rate drops off. It is worth again noting that, especially the last two of these, should have dedicated hardware interlocks to act as a fail-safe. Real-time analysis is not meant as a replacement for proper safety design, but can take action to avoid the need to replace thermal fuses. Additionally, it can notify the user that there has been a fault, and where the fault occurred.

4.2.1. Control Modules

To take preventative actions we must have some devices capable of effecting control over parts of the experiment. While we have focused on the monitoring uses of our sensor modules, they are equally capable of producing a control signal. Typical examples include controlling relays, as shown in Fig. 1, or triggering interlock circuits. Hence the modules provide a way to react to changes in the experiment, such as turn off a pump if a leak is detected.

The above control examples produce digital signals using the GPIO pins. The ESP8266 does not have an onboard digital-to-analog converter, but one can be formed with onboard pulse-width modulation and an output filter. This provides a way of also issuing analog control signals.

5. Comparison of data sources

As a demonstration of the capabilities of this system, Fig. 6 shows the voltage of a power supply as monitored by 4 different data sources, all connected to sensor modules. One channel of the ADS1115 external ADC, a Keysight 34401A 6.5-digit multi-meter, and the power supply (Keysight 6690A) itself are used to monitor the supply voltage to our quadrupole trapping coils, as shown in Fig. 7, and the temperature of our cooling water is monitored with a DS18B20. Both the multi-meter and the power supply are monitored via a GPIB connection from sensor modules (as pictured in Fig. 4). The external ADC is connected directly to the coil (without any conditioning), but is over-sampled by a factor of 10 and then averaged. Both the external ADC and the multi-meter are sensitive enough to pick up the drift in the power supply voltage as it attempts to source a constant 35 A current. The voltage fluctuations correlate highly...
with the temperature of the water cooling the coils, suggesting that we are observing the change of resistance due to temperature variation with a coefficient of $51.2(1) \mu \Omega \text{K}^{-1}$.

6. Conclusion

We have described a condition monitoring system targeted at the research laboratory. Our platform operates with a number of wireless sensor modules distributed around the lab. The modules are capable of monitoring with a variety of sensors, and also commercial (or home-built) instruments with analog or digital interfaces. The present work provides a vehicle for detecting equipment failures and for providing information that quickly highlights the point of failure. It also provides a framework for logging process parameters and operating points of the day-to-day running of the experiments in which drifts can predict the failure of some components.

We have considered the specific example of the ultracold atom experiment, but this system is suitable for a range of similarly complex experimental setups. Our system is easily deployed and detailed instructions are provided to do this [10], making collecting information about an experiment’s health a small investment. The code for this project [10] is open-source, and uses third-party open-source libraries and tools. We hope that work this will stimulate further development of this project.

Acknowledgements

We would like to thank Susanne Otto and Ryan Thomas for their testing and feedback on this system.

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Fig. 6. The voltage of the power supply for our quadrupole trap as measured from different sources. The power supply readout is not sensitive enough to detect the drifts which the external ADC and the 6.5 digit multimeter are able to detect. The signal from external ADC has much more variation. The temperature of the water in a storage tank in our cooling system is also shown. The power supply is operating in a constant current mode, so the voltage fluctuates with the temperature induced resistance change of the coil.

Fig. 7. A test configuration for our system. A power supply sources a current to our quadrupole electromagnets, trapping a cloud of cold atoms. The coil voltage is monitored by the power supply itself, a GPIB compatible multi-meter, and an ADS1115 ADC. The electromagnets are cooled by a recirculating water system (chiller and pumps not pictured), with the temperature of the coolant tank monitored.
Supplementary Material

The code and detailed documentation for this project forms the supplementary material [10].