An environmental monitoring network for quantum gas experiments and devices

Article (Published Version)

Barrett, Thomas, Evans, William, Gadge, Amruta, Bhumbra, Shobita, Slegers, Scott, Shah, Robert, Fekete, Julia, Orucevic, Fedja and Krüger, Peter (2022) An environmental monitoring network for quantum gas experiments and devices. *Quantum Science and Technology*, 7 (2). a025001 1-10. ISSN 2058-9565

This version is available from Sussex Research Online: <http://sro.sussex.ac.uk/id/eprint/104172/>

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:

Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

PAPER • OPEN ACCESS

An environmental monitoring network for quantum gas experiments and devices

To cite this article: T J Barrett *et al* 2022 *Quantum Sci. Technol.* **7** 025001

View the [article online](#) for updates and enhancements.

You may also like

- [Corrigendum: Radiative \$^{10}\text{Be}\(n, \gamma\)^{11}\text{Be}\$ capture at thermal and astrophysical energies \(2016 *J. Phys. G: Nucl. Part. Phys.* **43** 095201\)](#)
S B Dubovichenko and A V Dzhazairov-Kakhramanov
- [Discovery of ASKAP J173608.2–321635 as a Highly Polarized Transient Point Source with the Australian SKA Pathfinder](#)
Ziteng Wang, David L. Kaplan, Tara Murphy *et al.*
- [Investigation of the Timing and Spectral Properties of an Ultraluminous X-Ray Pulsar NGC 7793 P13](#)
Lupin Chun-Che Lin, Chin-Ping Hu, Jumpei Takata *et al.*

IOP | ebooks™

Bringing together innovative digital publishing with leading authors from the global scientific community.

Start exploring the collection—download the first chapter of every title for free.

Quantum Science and Technology

PAPER

OPEN ACCESS

RECEIVED
29 January 2021

REVISED
13 September 2021

ACCEPTED FOR PUBLICATION
26 October 2021

PUBLISHED
1 February 2022

Original content from
this work may be used
under the terms of the
[Creative Commons
Attribution 4.0 licence](#).

Any further distribution
of this work must
maintain attribution to
the author(s) and the
title of the work, journal
citation and DOI.

An environmental monitoring network for quantum gas experiments and devices

T J Barrett^{1,*} , W Evans¹ , A Gadge^{1,2} , S Bhumbra¹, S Slegers¹ , R Shah¹ ,
J Fekete¹ , F Oručević¹ and P Krüger¹

¹ Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, United Kingdom

² Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 761001, Israel

* Author to whom any correspondence should be addressed.

E-mail: T.J.Barrett@sussex.ac.uk

Keywords: atomic physics, quantum technology, environmental monitoring, Bose–Einstein condensate, cold atoms, electronics and software

Abstract

Quantum technology is approaching a level of maturity, recently demonstrated in space-borne experiments and in-field measurements, which would allow for adoption by non-specialist users. Parallel advancements made in microprocessor-based electronics and database software can be combined to create robust, versatile and modular experimental monitoring systems. Here, we describe a monitoring network used across a number of cold atom laboratories with a shared laser system. The ability to diagnose malfunction, unexpected or unintended behavior and passively collect data for key experimental parameters, such as vacuum chamber pressure, laser beam power, or resistances of important conductors, significantly reduces debugging time. This allows for efficient control over a number of experiments and remote control when access is limited.

1. Introduction

Recent developments in quantum technologies that exploit the unique properties of cold atomic clouds, such as gravimeters [1] and navigational accelerometers [2, 3], have been focused on producing miniature, field-based and remote systems. The challenging environmental conditions these systems are exposed to, as seen in space-borne experiments [4], can be mitigated using automated control sequences, with evolutionary algorithms and machine learning protocols becoming increasingly common [5–8]. The rapid resolution of problems is essential in inter-dependent networks [9] or in isolated remote systems where performance data may only be accessed infrequently, such as marine-based systems [10, 11].

Ultracold atom clouds are extremely sensitive to their environmental conditions due to having energy distributions on the nanokelvin scale. Typical laboratory-based systems experience drifts and instability caused by external environmental effects such as thermal disturbances and acoustic noise, which can affect a number of experimental components including mirrors, laser paths, coil resistances and power supplies used to generate magnetic fields. To mitigate these effects, it is possible to actively correct for individual issues with local feedback systems on parameters such as the polarisation of light beams [12], or the currents used to produce magnetic fields [13], for example.

Often, environmental measurements are subsequently collected after an error has occurred, to retrospectively determine the underlying cause. This can be cumbersome and events may not be easy to reproduce, causing further operational delays. Here, we present a laboratory monitoring network used to autonomously record a number of experimental parameters across a suite of ultracold atom laboratories continually in the background, and visualise them in real time which allows for a fast response to unexpected errors. The ability to efficiently process and record environmental data will be crucial as quantum technology devices become more complex, for example using Bose–Einstein condensates (BECs) instead of thermal clouds, or as they are exposed to more challenging environmental conditions where changes are unpredictable. The described system employs a number of measurement nodes to record a wide variety of relevant parameters, such as temperatures, vacuum chamber pressures, laser power levels, and

magnetic field strengths, as shown in figure 1(a). The sensors are networked together and data are recorded in an external time-series database (TSDB), which is then accessed through a series of end-user dashboards supported on an internet platform, an example of which is shown in figure 1(b).

Our network contributes to an emerging ecosystem of laboratory monitoring systems that provide both measurement and management of environmental data [14]. These database systems must be scalable, flexible and time-stamped for access in order to help users solve problems faster, and ideally remotely, facilitating experimental progress. The breadth of hardware and software tools that has been developed in the open source community means that monitoring systems can be designed for specific use, and implementation is straightforward. Improvements in the capability of programmable electronics [15–17] and expanding database infrastructure can be exploited for use in cold atom laboratories [18]. Microprocessor approaches have been implemented for control systems [19–21], locking systems [22, 23] and for environmental management [24]. Furthermore, such monitoring hardware can be integrated into feedback systems [25] and used with management software [24].

A similar advance has occurred in field programmable gate array (FPGA)-based hardware and has been followed by the development of FPGA-based control systems for atomic physics experiments [26, 27]. Additional advances in control systems [28] have allowed for the automation of experimental feedback [29], optimised control of complex sequences [30] and even citizen-science participation [31, 32]. Remote control of laboratory experiments is common in situations such as particle physics [33] and teaching laboratories to expand use of key equipment [34, 35]. Furthermore, as quantum technology approaches maturity, commercial systems are becoming available for remote non-specialist users through online portals [36, 37].

2. Data acquisition

A functional schematic of the entire monitoring network is depicted in figure 2. The system presented here has two types of measurement nodes: in the first type, data is ‘pushed’ by the node to the database as part of the analysis protocol. As is typical in atomic physics experiments, this means the acquisition of a series of images of the atomic cloud [38] to determine parameters such as atom number, cloud temperature, cloud shape, trap frequency, and more. Once these values are calculated, they are pushed directly to the database within the analysis programs. The second type of measurement nodes are microcontroller-based devices that locally acquire environmental measurements from various sensors around the laboratories when triggered via request over an isolated local area network (LAN), and as such data is ‘pulled’ from these nodes in this case by the ‘collector’ device. Organising the network in this way means that pulled environmental data is acquired in a synchronised manner with an update period set only by the collector device (in contrast to the atom cloud data, which is pushed whenever a new data point arrives). The vast array of microcontroller hardware available allows for each node to be configured to suit a range of requirements, and standardise data readings to conform to the database format. Current microprocessor hardware used here includes transimpedance amplifiers and photodiodes for measuring laser beam powers, Hall sensors for measuring magnetic field strengths, serial interfaces for communicating with devices such as vacuum gauges, and digital optocouplers for detecting the on/off states of equipment such as interlocks and shutters. The custom firmware written for all microcontrollers, schematics and designs for custom

electronics, and other software used in this network has been made publicly available at an online repository [39].

The existing ecosystem of microprocessor hardware is accessible, easy to implement, has community support available and elements can be integrated into custom devices to reduce the number of total components. For example, in the system presented here, a single printed circuit board (PCB) [39] was designed to consolidate eight thermocouple amplifiers and 12 transimpedance amplifiers that are used to record the temperature at various locations and laser beam powers at several points along the beam paths, respectively. In this case, the thermocouple amplifier chip (MAX31855K, Maxim Integrated) converts the thermocouple readings to digital form and outputs them using the standard serial peripheral interface communication protocol. Existing software communication libraries are available [40] (as with all sensors used here), which makes reading a temperature into an array possible with a single simple command `T[0] = thermocouple01.readCelsius()`. The availability of such software libraries facilitates fast setup of additional sensor nodes whenever required, for users with little programming experience.

The combination of different measurements is easily programmed and is carried out sequentially over each measurement node. Once a node receives a request for data from the collector device, it measures data from each of its attached sensors, collates them into a location-stamped string and returns this string via the LAN. There are over 100 sensors compiling environmental data across the devices in the system presented here. Messages are exchanged over a wired network to avoid wireless microwave noise interfering with the experiments—for instance, WiFi signals at 2.4 GHz and 5.0 GHz are close to the hyperfine ground states in alkali metals. The data are transferred via user datagram protocol (UDP), due to its simplicity and low-overhead, at intervals of 20 s, and was measured to have a 100% transfer efficiency over a week of operation. This update rate was found to be appropriate for monitoring environmental data, but can be reduced to the millisecond level with the current microprocessor hardware (and the TSDB itself is limited to nanosecond time-stamps). Data is transferred in UDP packets, which are both sent and received easily using functions from an existing software library, *EthernetUDP* [41]. For example, the collector device triggers a sensing node by sending a message simply by executing the commands `Udp.beginPacket(Node_IP, localPort); Udp.print("READ"); Udp.endPacket();` [39]. Finally, to preserve the robustness of communication, each device is programmed with a watchdog script to power-cycle reset should communication ever be lost, allowing them to automatically reconnect back to the network.

3. Database architecture

Once the individual measurements have been taken at local nodes and sensors in each laboratory and transferred to the collector microcontroller over UDP LAN, as described in the previous section, it is important that they are then reliably imported to a TSDB for storage and management. The collector is

connected directly to a ‘parser’ device, based on a Raspberry Pi, using a USB serial communication bridge, which allows a single point of contact from the isolated LAN to the outside internet. The collector transfers any received measurement strings over to the parser, at which point Python programming scripts [39] are used to parse the data strings into separate variables, standardise the format, and enter them into a TSDB. The database is an instance of the open-source tool *InfluxDB* [42], which is running elsewhere on a network server with a backup storage drive. InfluxDB provides an application programming interface (API), and we use the Python library *requests* [43] to easily post newly-parsed data to the hypertext transfer protocol endpoint of the API with commands of the form

```
requests.post("http://[IP]:[PORT]/write?db=[DB]", data=payload_string)
```

where the user inputs the IP address, port number, and database name of the InfluxDB instance.

The TSDB software was chosen because it is optimised to efficiently write, compress, and store data, while also keeping it readily available for fast querying. This is important when maintaining historical data over years of use. The format is easily scalable and data points can be tagged and grouped for simple management. InfluxDB query language is simple, easy to integrate into existing analysis code, and similar to existing database languages such as structured query language. Each data entry is stored in the database with general the form:

```
"Measurement Name", <tag_key1>=<tag_value>,<tag_key2>=<tag_value>
<field_key1>=<field_value>,<field_key2>=<field_value>
```

with the *tags* providing a way to add any relevant identifying labels to the measurements. Specifically, an example temperature measurement takes the following form:

```
"temperature", RoomID=Lab03, DevID=Dev01 T1=21.6, T2=22.8, T3=25.2.
```

Each monitoring node in a network system can be adapted to suit the necessary local measurements, leading to a complex data set which we process and organise according to tags during collection at the parser. A system of ten measurement nodes, capturing an average of ten measurements each at 20 s intervals, requires ~6.25 GB of storage space per year. All data is automatically time-stamped on entry, is backed up regularly, and retention policies are used to downsample historic data (>1 year) from every 20 s to hourly values to conserve storage space.

Data visualisation tools are invaluable for interpretation of the stored data by general users not having detailed knowledge of the database scheme. Here, we use an open-source tool called Grafana [44], which has native support for direct integration with a TSDB. This combination of tools has been used for an expansive range of complex systems, from bee keeping [45] to financial monitoring [46]. We use the visualisation tool to allow users to build customised dashboards for displaying relevant metrics in a web browser from any remote location with an internet connection. This includes dashboards for different combinations of any measurements from several nodes across the network of laboratories—for example, in our setup we have a dashboard dedicated to displaying beam powers at several points along the chain of a shared laser system, over multiple rooms, to monitor stability at each point. Users can quickly look back at charts of data over any time period or see the overall system health at a glance rather than setting up additional time consuming measurements following an error.

For critical measurements the system is programmed to send an alert to users if a threshold is reached, for example if the temperature of a vacuum system rises too quickly during a bake out process which can damage components, or if the seed light injecting a tapered amplifier laser is too high or low. The ability to continuously assess a range of experimental parameters with one central database simplifies maintenance procedures which, if ignored, can otherwise cause long delays in experiments.

4. Distributed laser system

One example of the type of experimental infrastructure that can benefit from integration with a monitoring network is a collection of shared lasers. In our system, a pair of tapered amplifier lasers are used to provide the two central laser frequencies employed by a suite of three atomic physics laboratories, where this seed light is then locally amplified. Each laser is locked to an atomic reference in the central laboratory, split into individual paths for each experiment and then distributed to the laboratories via single-mode polarisation-maintaining optical fibers, as indicated in figure 2 (top-left corner). The ability to monitor properties of the light at several points along each path allows for fast debugging when necessary.

Figure 3. (a) A collection of environmental measurements taken from the TSDB and experimental parameters calculated from image analysis during a repeated experimental run over two and a half hours. (b) An example correlation matrix calculated for the monitoring data above showing Pearson coefficients. There are strong correlations between the cloud position in both horizontal (H) and vertical (V) directions with the power in the absorption imaging probe beam. However, there are only strong correlations between the cloud V position and the output power of the local laser amplifier, showing that the cloud position is more sensitive to the laser power in this direction. The strongest correlations with atom number are seen in the local laser output power and central laser laboratory temperature, which highlight problems due to fluctuations in seed power introduced during fiber coupling.

The optical power of the laser beams is monitored both in the centralised laser laboratory and in the individual science laboratories to assess the stability and detect changes in fiber coupling efficiencies. This is also important for the protection of the local amplifier chips which can be damaged if operated when the seed power is measured to be above or below a given threshold. Therefore, watchdog safety circuits, which switch off the amplifier if seed power deviates outside a preset range, have been implemented measuring both the input seed powers with in-fibre photodiodes and amplifier output powers. Additionally, these circuits are integrated with interlock safety systems in each individual laboratory. The monitoring system is supplemented with local active feedback on the amplifier current, which is able to mitigate small drifts in the laser properties due to polarisation drift in the delivery fibers [47, 48] and provide stable output power. This demonstrates the interaction between the monitoring system and local hardware to provide suitable protection and feedback.

The ability to monitor laser powers at each point in the chain of this system, using a centralised dashboard, significantly reduces the time taken to rectify issues with coupling and frequency stability. This allows for simultaneous monitoring of a number of laboratories by a single user which paves the way for implementation of distributed networks of quantum technology devices, such as a network of gravimeters for gravitation-wave detection [49].

5. Integration with experimental data

Current quantum technology devices have focused on using thermal atomic clouds but there are schemes which employ BECs for a greater sensitivity in gravimetry [50, 51] or a finer resolution in microscopy [52, 53]. To generate BECs, we evaporatively cool a magnetically trapped cloud of atoms using radio-frequency (RF) radiation to a temperature below the critical value, typically on the order of merely hundreds of nanokelvin, which requires precise control of the atoms over an experimental cycle that is on the order of a few seconds to a minute. In addition to this, in order to perform long-term experiments with BECs and gather statistics, the system must run in a stable, repeatable way over at least a course of several hours. Such experiments are extremely sensitive to the external environment which, while making it challenging to produce BECs, provides substantial performance benefits for quantum sensors over their classical equivalents.

Experimental systems designed for producing BECs involve complex parameter spaces. For example, just one laboratory in our system uses eight laser frequencies combined pairwise into eight beams, delivered to two different vacuum regions, using 15 power supply currents, and three distinct stages of applied RF radiation. With our monitoring system recording many of these critical parameters in the background, the centralised database of measurements is easily accessed independently to download any specific time series. Additionally, since the experimental observables are also ‘pushed’ to the database whenever they are

calculated, as was indicated in figure 2, we are able to easily obtain the environmental measurements alongside the atom numbers, cloud temperatures, positions, and more, over any time period, allowing for simple debugging and stability studies of the entire system. The data can be downsampled and viewed on different timescales as needed to show both short-term and long-term variations.

An example showing the collated raw monitoring system data for a magneto-optical trap (MOT) stage—one of the pre-cooling stages in a BEC experiment, when the atoms are still at a temperature of several 100 microkelvin—is presented in figure 3(a). There are a variety of signal processing techniques which can be applied to characterise the correlations between the captured signals. As an example, in figure 3(b) we characterise the linear dependence between the variables by constructing a correlation matrix of Pearson coefficients, which is a scaled covariance, as this technique highlights large correlations that can point to specific experimental problems. For example, both the horizontal (H) and vertical (V) cloud positions are strongly correlated with the power in the absorption imaging beam used to probe the atomic sample (probe power), which in turn is derived from the main laser. The atom number has its largest correlations with local laser output power and temperature in the central laser laboratory, which was traced back to sub-optimal optical fiber coupling alignment and associated polarisation drifts.

At this point, with access to such data, further techniques could be used for identifying a more abstract analysis that best describes the entire system. Here however, we maintained the original variables throughout for simplicity, as it was found to be sufficient for the inspection and debugging process. Nevertheless, for example, time-lagged linear dependencies would be uncovered by using cross-correlations to find phase differences. Similarly, frequency responses and correlations in frequency space could be determined by comparing each signal's power spectral density from a discrete Fourier analysis. Furthermore, the analysis of such a wide data set can be extended in detail using machine learning techniques and principal component analysis [54].

We now turn to the example of a much colder cloud, just above the phase transition temperature to BEC, which is a system particularly sensitive to variations in the external environment. Examples of aggregated data from the monitoring system for such a system are shown in figure 4. In this measurement, ^{87}Rb atoms are spin-polarized in the $|F = 2, m_F = +2\rangle$ magnetic sub-state and confined in an harmonic Ioffe–Pritchard style trap, which is created by passing electrical current through a Z-shaped wire together with two external homogeneous bias fields (denoted X-bias and Y-bias) [55]. The atoms are then prepared at a temperature of around 1.6 μK by an RF evaporative cooling sweep down to a fixed frequency, thereby truncating the trap depth [56]. The most critical properties of the cloud, namely atom number and temperature, are extracted through optical absorption imaging with a resonant probe beam [38], and the procedure was repeated every 20 s with a new atomic sample in order to examine the stability of the experimental system.

It can be seen in figures 4(a) and (b) that the cloud exhibits significant instability and drifts over the first 6 h. Specifically, a peak-to-peak variation of 40% of the total atom number, and 0.7 μK in the cloud temperature are observed. Such variations of the important observables are known to be a common

problem for experimental ultracold systems, and it is crucial to track down and mitigate those instabilities at their source. At this point, the action taken would typically be to begin collecting data to identify the contributing quantities, which requires significant additional time and resources. It is in exactly this type of situation where an environmental monitoring system becomes an extremely useful tool. In this case, since the system is continually collecting data from a variety of sensors we were able to simply retrieve a range of measurements from the relevant time period, to uncover the source of the problem.

Figure 4(c) shows such collected data from measurements of the electrical currents used to drive the Z-shaped wire (I_{Zw}) and the two coils generating the orthogonal homogeneous bias fields (I_X and I_Y), which combine together to create the trapping potential for the atom cloud. The currents are continually measured with a series of fluxgate-based electrical current transducers (LEM CASR 50-NP). In contrast to the atom number drifts, a variation of up to several 100 milliamps that is more periodic in nature is apparent for all three currents, and no one individual current appears obviously responsible. The periodic variation is in turn identified to be caused by the ambient laboratory temperature (also plotted in figure 4(c)). However, the *ratio* of I_X/I_{Zw} has been plotted in addition on figures 4(a) and (b), and is well-correlated with both the atom number and temperature. This can be understood because, by the construction of the trapping configuration, the ratio of the two currents I_X and I_{Zw} is in fact responsible for prescribing the value of the magnetic field at the trap bottom. Therefore, since the absolute final RF cooling frequency is fixed, a trap bottom change results in a trap depth change, and ultimately to a loss of higher energy atoms and an associated reduction in cloud temperature. In contrast, the remaining current I_Y primarily controls the position of the trap minimum, and has only a very weak effect on the field at the trap bottom.

After identifying the largest contribution to the cloud variations, we implemented a simple feedback system for the electrical currents by combining information of the measured currents with the voltages applied across the loads to obtain the instantaneous resistances of each conductor, and adjust the power supply voltages as necessary to minimise variations in currents for each experimental cycle. The results after activating the feedback can be seen during the second six-hour period of figure 4, showing that the peak-to-peak variations have been reduced to 15% of the total for the atom number (a factor of 2.7 improvement), and to $0.35\ \mu\text{K}$ for the cloud temperature (a factor of 2 improvement), in spite of the ambient laboratory temperature continuing to vary as before. This workflow demonstrates that the ability to concurrently measure multiple environmental parameters in tandem with experimental observables allows for targeted improvements of experimental performance without the need for a large series of independent measurements retrospectively.

Furthermore, the data captured with the monitoring system allows for continuous comparison of the experiment under different environmental conditions. The example in figure 5 shows the increase of the atom number in a BEC, permitted due to better optimisation and more stable environmental parameters. After the first eight-hour period of collecting measurements, the local air-conditioning system was

deactivated, to investigate its effect. It can be seen firstly that the overall ambient temperature increased, and secondly that the saw-tooth behavior in the temperature profile—characteristic of bang–bang style (on/off) feedback controllers in commercial air conditioning systems [57]—has been eliminated. The room temperature in turn affects the vacuum chamber pressure, and the overall effect is an increase in the atom number (along with a reduction in variation) in the magnetic trap just above the transition temperature from $(2.2 \pm 0.6) \times 10^6$ to $(4.8 \pm 0.3) \times 10^6$. This ultimately results in a much larger atom number in the final BEC, illustrated in figure 5(b).

These examples show the benefit of having access to regular environmental data to improve experimental performance by optimising the system to the most stable background conditions. The ability to autonomously monitor a series of relevant variables, including power supply currents, conductors' resistances, and laser powers, is key to allow experimental development even with limited laboratory access for debugging, as for in-field devices or up-scaled quantum technologies. Using this system allowed one of our laboratories to advance an experiment from using thermal clouds to producing BECs without physical access to the laboratory during the Covid-19 pandemic in 2020.

6. Conclusion

The accessible and flexible monitoring system presented here provides a useful blueprint for replication in similar cold atom laboratories. The ability to continually measure key experimental parameters and centralise data storage across a network of experiments paves the way for consolidated control and shared infrastructure, demonstrated by the distributed laser system. The time-stamped database system allows a wide range of measurements from various sources to be aggregated into one place in a standardised format and presented to end users with versatile dashboards, enabling the general health of the experiments to be assessed at a glance. This reduces the time needed for problem solving from days or hours down to minutes or seconds, and eases the progression of experiments, shown here by the remote creation of a BEC in an experiment which did not previously have one. We have demonstrated the usefulness of such a monitoring system in identifying the sources of long-term instabilities for both a MOT and a magnetically-trapped ultracold atomic cloud just above the phase transition temperature to BEC, as well as the benefits emerging from the ability to monitor and optimise a BEC itself. The matrix of correlation coefficients illustrates how the real-time analysis of experimental and environmental parameters can highlight seemingly unintuitive dependencies. The integration of such analytical tools is essential in democratising quantum technologies as they assist the end-users without specialist knowledge in quantum physics in operating and maintaining complex systems. The data management infrastructure presented here can be employed in a wide range of quantum setups, including large networks of atomic experiments or remote systems where access is limited, in a laboratory context or in the field.

Data availability

Further details required to reproduce the system described here have been made publicly available at an online repository [39]. This includes: datasheets of commercial devices integrated into our system; schematic and PCB production drawings (Gerber and NC drill files) for bespoke electronic circuits; microprocessors' firmware; parser python scripts; and a collection of user guides and reports written by authors detailing the implementation and integration of individual system components.

ORCID iDs

T J Barrett <https://orcid.org/0000-0001-7997-4446>

W Evans <https://orcid.org/0000-0001-8323-0722>

A Gadge <https://orcid.org/0000-0002-0722-2015>

S Sleepers <https://orcid.org/0000-0001-5322-6810>

R Shah <https://orcid.org/0000-0002-7884-1534>

J Fekete <https://orcid.org/0000-0002-6027-1289>

F Oručević <https://orcid.org/0000-0002-6114-4580>

P Krüger <https://orcid.org/0000-0001-9908-6454>

References

- [1] Mnoret V, Vermeulen P, Le Moigne N, Bonvalot S, Bouyer P, Landragin A and Desruelle B 2018 Gravity measurements below 10–9 g with a transportable absolute quantum gravimeter *Sci. Rep.* **8** 12300
- [2] Cheiney P, Fouch L, Templier S, Napolitano F, Battelier B, Bouyer P and Barrett B 2018 Navigation-compatible hybrid quantum accelerometer using a Kalman filter *Phys. Rev. Appl.* **10** 034030
- [3] Garrido Alzar C L 2019 Compact chip-scale guided cold atom gyrometers for inertial navigation: enabling technologies and design study *AVS Quantum Sci.* **1** 014702
- [4] Becker D *et al* 2018 Space-borne Bose–Einstein condensation for precision interferometry *Nature* **562** 391–5
- [5] Wigley P B *et al* 2016 Non-destructive shadowgraph imaging of ultra-cold atoms *Opt. Lett.* **41** 4795
- [6] Geisel I, Cordes K, Mahnke J, Jllenbeck S, Ostermann J, Arlt J, Ertmer W and Klempt C 2013 Evolutionary optimization of an experimental apparatus *Appl. Phys. Lett.* **102** 214105
- [7] Tranter A D *et al* 2018 Multiparameter optimisation of a magneto-optical trap using deep learning *Nat. Commun.* **9** 4360
- [8] Barker A J, Style H, Luksch K, Sunami S, Garrick D, Hill F, Foot C J and Bentine E 2020 Applying machine learning optimization methods to the production of a quantum gas *Mach. Learn.: Sci. Technol.* **1** 015007
- [9] Canuel B *et al* 2020 ELGAR-a European laboratory for gravitation and atom-interferometric research *Class. Quantum Grav.* **37** 225017
- [10] Bidet Y, Zahzam N, Blanchard C, Bonnin A, Cadoret M, Bresson A, Rouxel D and Lequentrec-Lalancette M F 2018 Absolute marine gravimetry with matter-wave interferometry *Nat. Commun.* **9** 627
- [11] Zatezalo A, Vuleti V, Baker P and Poling T C 2008 Bose–Einstein interferometry and its applications to precision undersea navigation 2008 *IEEE/Ion Position, Location and Navigation Symp.* pp 940–50
- [12] Hidayat A, Koch B, Zhang H, Mirvoda V, Lichtinger M, Sandel D and No R 2008 High-speed endless optical polarization stabilization using calibrated waveplates and field-programmable gate array-based digital controller *Opt. Express* **16** 18984
- [13] Thomas R and Kjrgaard N 2020 A digital feedback controller for stabilizing large electric currents to the ppm level for Feshbach resonance studies *Rev. Sci. Instrum.* **91** 034705
- [14] Gurdita A, Vovko H and Ungrin M 2016 A simple and low-cost monitoring system to investigate environmental conditions in a biological research laboratory *PLoS One* **11** e0147140
- [15] Grinias J P, Whitfield J T, Guetschow E D and Kennedy R T 2016 An inexpensive, open-source USB Arduino data acquisition device for chemical instrumentation *J. Chem. Educ.* **93** 1316–9
- [16] Kubnov S and Slgr J 2015 ChemDuino: adapting Arduino for low-cost chemical measurements in lecture and laboratory *J. Chem. Educ.* **92** 1751–3
- [17] Zachariadou K, Yiasemides K and Trougakos N 2012 A low-cost computer-controlled Arduino-based educational laboratory system for teaching the fundamentals of photovoltaic cells *Eur. J. Phys.* **33** 1599–610
- [18] Chilcott M and Kjrgaard N 2021 Low-cost wireless condition monitoring system for an ultracold atom machine *Internet Things* **13** 100345
- [19] Malek B S, Pagel Z, Wu X and Mller H 2019 Embedded control system for mobile atom interferometers *Rev. Sci. Instrum.* **90** 073103
- [20] Eyler E E 2011 A single-chip event sequencer and related microcontroller instrumentation for atomic physics research *Rev. Sci. Instrum.* **82** 013105
- [21] Deng W, Yun P, Zhang Y, Chen J and Gu S 2012 Embedded control system for atomic clock *Knowledge Discovery and Data Mining* ed H Tan (Berlin: Springer) pp 61–7
- [22] Eyler E E 2013 Instrumentation for laser physics and spectroscopy using 32-bit microcontrollers with an Android tablet interface *Rev. Sci. Instrum.* **84** 103101
- [23] Huang K, Le Jeannic H, Ruaudel J, Morin O and Laurat J 2014 Microcontroller-based locking in optics experiments *Rev. Sci. Instrum.* **85** 123112
- [24] Jiang L, Zhu Z, Li H and Guo Z 2009 Embedded laboratory environment monitor system 2009 *WASE Int. Conf. Information Engineering, ICIE 2009* vol 2 pp 197–201
- [25] Mondal R and Pal S 2013 Microcontroller based temperature monitoring and closed loop control to study the reaction of controlled variable with respect to load changes *Sens. Transducers* **153** 148–54
- [26] Bourdeauducq S *et al* 2016 ARTIQ 1.0 Zenodo
- [27] Perego E, Pomponio M, Detti A, Duca L, Sias C and Calosso C E 2018 A scalable hardware and software control apparatus for experiments with hybrid quantum systems *Rev. Sci. Instrum.* **89** 113116
- [28] Keshet A and Ketterle W 2013 A distributed, graphical user interface based, computer control system for atomic physics experiments *Rev. Sci. Instrum.* **84** 015105
- [29] Starkey P T, Billington C J, Johnstone S P, Jasperse M, Helmerson K, Turner L D and Anderson R P 2013 A scripted control system for autonomous hardware-timed experiments *Rev. Sci. Instrum.* **84** 085111
- [30] Amri S, Corgier R, Sugny D, Rasel E M, Gaaloul N and Charron E 2019 Optimal control of the transport of Bose–Einstein condensates with atom chips *Sci. Rep.* **9** 5346
- [31] Heck R *et al* 2018 Remote optimization of an ultracold atoms experiment by experts and citizen scientists *Proc. Natl Acad. Sci. USA* **115** E 11231–7
- [32] Laustsen J S, Heck R, Elsson O, Arlt J J, Sherson J F and Weidner C A 2021 Remote multi-user control of the production of Bose–Einstein condensates for research and education (arXiv:2101.11398)
- [33] Krause H F, Deveney E F, Jones N L, Vane C R, Datz S, Knudsen H, Grafstrm P and Schuch R 1997 Novel apparatus and methods for performing remotely controlled particle-solid interaction experiments at CERN *Nucl. Instrum. Methods Phys. Res. B* **124** 128–39
- [34] Hyder A, Choi S K and Schaefer D 2010 Remotely controlled laboratory experiments: creation and examples 2010 *IEEE Systems and Information Engineering Design Symp. SIEDS10* pp 62–7
- [35] Sharafutdinova G, Cvetanovski M, Walton D, Guest B, Foster J, Piszczuk G and Furst J 2013 Distance learning laboratory: a remote atomic and nuclear physics experiment *Aust. Phys.* **50** 55–9
- [36] ColdQuanta Inc. 2020 Albert: quantum matter on the cloud <https://coldquanta.com/albertcloud>
- [37] IBM Quantum Team 2020 IBM quantum experience <https://quantum-computing.ibm.com>
- [38] Smith D A *et al* 2011 Absorption imaging of ultracold atoms on atom chips *Opt. Express* **19** 8471

- [39] Barrett T J 2021 An environmental monitoring network for quantum gas experiments and devices <https://github.com/tjb36/Barrett2021%20Monitoring%20Network>
- [40] Adafruit Industries 2015 *Adafruit MAX31855 library* <https://github.com/adafruit/Adafruit-MAX31855-library>
- [41] Arduino 2019 *Ethernet library reference* <https://arduino.cc/en/Reference/EthernetUDPBegin>
- [42] InfluxData Inc. 2021 InfluxDB: purpose-built open source time series database <https://influxdata.com>
- [43] Reitz K 2011 Python requests library <https://docs.python-requests.org/en/master/>
- [44] Grafana Labs 2021 Grafana: the open observability platform <https://grafana.com>
- [45] The Hiveeyes Developers 2011 The Hiveeyes project <https://hiveeyes.org>
- [46] A Young Programmer 2017 Grafana Finance <https://github.com/ayoungprogrammer/grafana-finance>
- [47] Kyselak M, Dvorak F, Maschke J and Vlcek C 2017 Phase response of polarization-maintaining optical fiber to temperature changes *Opt. Appl.* **47** 635–49
- [48] Eickhoff W 1981 Temperature sensing by mode-mode interference in birefringent optical fibers *Opt. Lett.* **6** 204
- [49] Badurina L *et al* 2020 AION: an atom interferometer observatory and network *J. Cosmol. Astropart. Phys.* **JCAP05(2020)011**
- [50] Aguilera D N *et al* 2014 Erratum: STE-QUEST-test of the universality of free fall using cold atom interferometry (2004 *Class. Quantum Grav.* **31** 115010) *Class. Quantum Grav.* **31** 159502
- [51] Dimopoulos S, Graham P W, Hogan J M and Kasevich M A 2007 Testing general relativity with atom interferometry *Phys. Rev. Lett.* **98** 111102
- [52] Wildermuth S, Hofferberth S, Lesanovsky I, Haller E, Andersson L M, Groth S, Bar-Joseph I, Krüger P and Schmiedmayer J 2005 Microscopic magnetic-field imaging *Nature* **435** 440
- [53] Gierling M, Schneeweiss P, Visanescu G, Federsel P, Häffner M, Kern D P, Judd T E, Günther A and Fortágh J 2011 Cold-atom scanning probe microscopy *Nat. Nanotechnol.* **6** 446–51
- [54] Segal S R, Diot Q, Cornell E A, Zozulya A A and Anderson D Z 2010 Revealing buried information: statistical processing techniques for ultracold-gas image analysis *Phys. Rev. A* **81** 053601
- [55] Reichel J, Hänsel W and Hänsch T W 1999 Atomic micromanipulation with magnetic surface traps *Phys. Rev. Lett.* **83** 3398–401
- [56] Davis K B, Mewes M-O, Joffe M A, Andrews M R and Ketterle W 1995 Evaporative cooling of sodium atoms *Phys. Rev. Lett.* **74** 5202–5
- [57] Al-Azba M, Cen Z, Remond Y and Ahzi S 2020 An optimal air-conditioner on-off control scheme under extremely hot weather conditions *Energies* **13** 1–21