Lab::Measurement—A portable and extensible framework for controlling lab equipment and conducting measurements


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Lab::Measurement is a framework for test and measurement automatization using Perl 5. While primarily developed with applications in mesoscopic physics in mind, it is widely adaptable. Internally, a layer model is implemented. Communication protocols such as IEEE 488 [1], USB Test & Measurement [2], or, e.g., VXI-11 [3] are addressed by the connection layer. The wide range of supported connection backends enables unique cross-platform portability. At the instrument layer, objects correspond to equipment connected to the measurement PC (e.g., voltage sources, magnet power supplies, multimeters, etc.). The high-level sweep layer automates the creation of measurement loops, with simultaneous plotting and data logging. An extensive unit testing framework is used to verify functionality even without connected equipment. Lab::Measurement is distributed as free and open source software.

Program summary
Program Title: Lab::Measurement 3.660
Program Files doi: http://dx.doi.org/10.17632/d8rgrdc7tz.1
Program Homepage: https://www.labmeasurement.de
Licensing provisions: GNU GPL v2
Programming language: Perl 5

Nature of problem: Flexible, lightweight, and operating system independent control of laboratory equipment connected by diverse means such as IEEE 488 [1], USB [2], or VXI-11 [3]. This includes running measurements with nested measurement loops where a data plot is continuously updated, as well as background processes for logging and control.

Solution method: Object-oriented layer model based on Moose [4], abstracting the hardware access as well as the command sets of the addressed instruments. A high-level interface allows simple creation of measurement loops, live plotting via GnuPlot [5], and data logging into customizable folder structures.


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1. Introduction

Experimental physics frequently relies on complex instrumentation. While high-level equipment often has built-in support for automation, and while more and more ready-made solutions for complex workflows exist, the nature of experimental work lies in the development of new workflows and the implementation of new ideas. A freely programmable measurement control system is the obvious solution.

One of the most widely used applications of this type is National Instruments LabVIEW [1], where programming essentially means drawing the flowchart of your application. While this is highly flexible and supported by many hardware vendors, more complex use cases can easily lead to flowcharts that are difficult to understand and to maintain. A second widely used commercial application implementing instrument control is MathWorks MATLAB [2], where this ties into its numerical data evaluation and graphical user interface (GUI) capabilities.

Lab::Measurement provides a lightweight, open source alternative to Perl 5, a well-known and well-established script programming language with a strong emphasis on text manipulation. Lab::Measurement has been successfully used for quantum transport measurements on GaAs/AlGaAs gate-defined quantum dots, see, e.g., [3–5], as well as carbon nanotube devices [6–8] and other mesoscopic systems [9,10].

As other open source measurement packages, see e.g. [11,12], Lab::Measurement features a modular structure which facilitates adding new hardware drivers. Here we highlight the unique features of Lab::Measurement. This includes in particular its high-level, descriptive “sweep” interface, where data and metadata preservation as well as real-time plotting is intrinsically provided. Notable is further the automated creation of unit tests via connection testing, and the use of traits [13] to exploit the modular structure of SCPI [14] and thereby minimize code duplication.

2. Implementation and architecture

Lab::Measurement is implemented as an object-oriented layer structure of Perl modules, as displayed schematically in Fig. 1. The figure does not show the full set of provided modules, but demonstrates a small selection of hardware.

The uppermost layer depicted in the figure, corresponding to the hardware driver, is not part of the Lab::Measurement Perl module distribution. Several Perl binding modules such as Lab::VISA (comparable to the Python PyVISA module [15]), Lab::VXI11, Lab::Zhinst, and USB::TMC are separately provided by the Lab::Measurement authors via the Comprehensive Perl Archive Network (CPAN), as bindings to third-party libraries. Conversely, e.g., the LinuxGPIB package [16] provides a Perl interface to its library and Linux kernel modules on its own.

The connection layer provides a unified API to these hardware drivers, making it possible to address devices, send commands, and receive responses. It handles access to many common automation protocols, such as GPIB, USB-TMC, VXI-11, raw TCP Sockets, or for example the Zurich Instruments LabOne API.

An overview of the currently supported connection types is given in Table 1.

The instrument layer represents connected test and measurement devices. The generic instrument class Lab::Moose::Instrument only provides means to send commands and receive responses; derived classes encapsulate the model-specific command sets. On this level, direct device programming can take place.

The Perl ecosystem. This means that it can be used and distributed according to the terms of either the GNU General Public License (version 1 or any later version) or the Artistic License; the choice of license is up to the user.

package Lab::Moose::Instrument::SR830;
use Moose;
use Lab::Moose::Instrument qw/validation_setter

Listing 1: Commented excerpt from the driver module for the Stanford Research SR830 lock-in amplifier; shown are the header and initialization, the functions for getting and setting the reference voltage frequency, and a function for reading out radius and phase of the measured signal.

The sweep layer finally provides abstraction of sweeping instrument parameters and performing multi-dimensional measurements, with live plotting and data logging. This facilitates the creation of complex measurement tasks for non-programmers without creation of loops or conditional control flow statements.

3. Extending and programming the instrument layer

3.1. Minimal example of an instrument driver

Listing 1 shows a commented excerpt of an instrument driver module, based on the Stanford Research SR830 lock-in amplifier module distributed with Lab::Measurement.

Low level functionality in drivers is frequently implemented via Moose roles. These are an implementation of the concept of traits, which enable horizontal code reuse more efficiently than single inheritance, multiple inheritance, or mixins [13,17]. In our case, roles are used to share functions between different instrument drivers. This significantly eases implementation of new drivers compared to other open-source measurement frameworks, e.g., [11,12]. The minimal driver of Listing 1 only consumes a single role, Lab::Moose::Instrument::Common, providing, e.g., the
Fig. 1. Schematic of the internal structure of Lab::Measurement. The gray frame indicates modules that are part of the Lab::Measurement Perl distribution. For this example, as instrument hardware a Keysight 34470A digital multimeter, an Oxford Instruments Mercury iPS superconducting magnet controller, and a Rohde & Schwarz ZVA vector network analyzer are chosen.

Table 1
Available protocols and corresponding connection types. National Instruments (NI) VISA is only supported by NI on few Linux distributions and faces severe functional restrictions there due to the requirement of loading proprietary Linux kernel modules. In particular, USB GPIB adaptors are not supported by NI VISA on Linux.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Connection name</th>
<th>Operating system support</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VISA</td>
<td>VISA</td>
<td>X</td>
<td>National Instruments VISA architecture device access</td>
</tr>
<tr>
<td>GPIB</td>
<td>LinuxGPIB</td>
<td>X</td>
<td>IEEE 488 / GPIB adaptors supported by the LinuxGPIB project</td>
</tr>
<tr>
<td></td>
<td>VISA::GPIB</td>
<td>(X)</td>
<td>IEEE 488 / GPIB frontend for VISA</td>
</tr>
<tr>
<td>IP, TCP</td>
<td>Socket</td>
<td>X</td>
<td>IP network sockets, mostly used for TCP connections</td>
</tr>
<tr>
<td>VXI-11</td>
<td>VXI11</td>
<td>X</td>
<td>VXI-11 protocol via SunRPC or libtirpc</td>
</tr>
<tr>
<td></td>
<td>VISA::VXI11</td>
<td>X</td>
<td>VXI-11 frontend for VISA</td>
</tr>
<tr>
<td>USB T&amp;M</td>
<td>USB</td>
<td>X</td>
<td>USB Test &amp; Measurement class device driver using libusb</td>
</tr>
<tr>
<td></td>
<td>VISA::USB</td>
<td>(X)</td>
<td>USB Test &amp; Measurement frontend for VISA</td>
</tr>
<tr>
<td>ZI LabOne</td>
<td>ZHinst</td>
<td>X</td>
<td>Zurich Instruments LabOne API</td>
</tr>
</tbody>
</table>

The code in the BUILD method is executed after instrument construction. Here we clear the device input and output buffers and any status or error flags. Otherwise we take care that driver initialization does not change any further device state; this is to ensure that, e.g., output voltages do not fluctuate on script start, or that manually applied configuration settings are kept unless explicitly overridden in the script.

The following code handles reading and setting the frequency of the ac voltage generated at the lock-in reference output. Hardware access is often slow, in particular regarding query operations, which is why we declare a cache for the frequency using functionality from Lab::Moose::Instrument::Cache. The cache keeps track of frequency values written to the instrument, for fast later access. This assumes that device access is exclusive to the running script and no modifications on, e.g., a hardware front panel are taking place.

get_frq is provided to obtain the ac frequency of the reference signal generated by the lock-in amplifier. It can be called with a hash of options as argument, which is validated by validated_getter and passed to the instrument query function. The queried value of the frequency is cached and returned to the caller. set_frq sets the reference output ac frequency of the lock-in amplifier. It is called with a hash, which must contain a key named value that provides the frequency value. The frequency is set by writing the corresponding command to the instrument; subsequently the cache is updated with the frequency value.

The last stored cache value of the frequency can be accessed by the user with the cached_frq method. If this method is called when the cache entry is still empty, the getter method declared with the cache keyword, get_frq, is called to populate the cache. In effect, cached_frq should be used in high-level functions whenever possible, except for situations where a hardware query needs to be enforced (refreshing the cache) with get_frq.

As opposed to the reference frequency, the signal amplitude and phase are not device parameters but measured values and thus cannot be set; the get_rphi function performs no caching. It returns a reference to a hash with keys x and phi. In general, a design choice of Lab::Measurement is that functions always return a scalar variable; either directly a scalar value as, e.g., a frequency or a measured current, or a reference to a more complex Perl object.

The full SR830 driver contains several additional but similarly implemented functions. This includes controlling reference ac voltage amplitude, time constant, filter settings, input configuration, and sensitivity as well as reading out the signal as x- and y-quadrature or even as simultaneous combination (x, y, r, \(\varphi\)). The functions are documented in POD syntax; the documentation can, e.g., be read locally using perldoc or online on CPAN.
3.2. Example instrument driver based on SCPI roles

Listing 2 provides an example of a more complex instrument driver module, at the example of a Rohde & Schwarz (R&S) FSV series spectrum analyzer. The driver strongly relies on the role functionality of Moose. The roles included in the R&S FSV driver with the `with qw()` statement mostly model the SCPI subsystems [14] which comprise the command syntax of the instrument.

The high-level get_spectrum method, central part of the driver module, initiates a frequency sweep, reads the resulting spectrum from the instrument, and returns the data as a 2D array to the user. In the following, we discuss at its example how the different code parts interact in this method.

The FSV spectrum analyzer can be configured to record and store up to 6 frequency sweeps (called traces); the trace parameter can be used to address one of these. The precision parameter selects between double and single floating point precision as defined in the SCPI standard. The variable $freq_array is initialized with an array of the frequency values addressed within a sweep; then the device is configured to perform only one sweep (instead of continuous, repeated measurement).

After calculating the size of the resulting data block, the sweep is started by calling the initiate_continuous method, provided by the Lab::Moose::Instrument::SCPI::Initiate role. Calling the wai method from Instrument::Common (corresponding to the IEEE 488.2 command of the same name) waits until the device is ready. Due to the configuration, the implemented sweep is 6 traces with an array of the frequency values addressed within a sweep.

The block_to_array method provided by the Instrument::SCPIBlock role is used to convert the raw IEEE 488.2 binary block data into a Perl array. The array is then subsequently converted into a PDL (Perl Data Language) object, combined with the frequency array, and returned to the caller of the get_spectrum method. The returned PDL object can then be used for further processing or can be written to a datafile.

3.3. Instrument layer usage

The instrument layer is the lowestmost layer typically used in measurement scripts. All functions of an instrument driver can here directly be accessed, allowing fine-grained control and specialized programming. At the same time, the connection abstraction is present, allowing instrument control independent of the precise operating system of the control PC running Lab::Measuremiment or the wiring.

Listing 3 shows a brief example how to read out a Stanford Research SR830 lock-in amplifier connected via LinuxGPIB, using the driver discussed above. It sets the amplitude and frequency of the lock-in reference output. The new values are queried and printed together with the amplitude and phase of the measured signal.

Note that, as a consequence of abovementioned coding convention, get_rphi returns a scalar, namely a hash reference; the returned values are thus accessed as, e.g., $rphi->{r} and $rphi->{phi}.

4. Sweep layer usage

A complete example of a measurement script based on the Lab::Moose::Sweep interface is given in Listing 4. It is intended for a magnetic resonance experiment, where, e.g., a ferromagnetic sample is mounted on a coplanar waveguide and microwave...
transmission is measured as a function of applied magnetic field. The magnetic field is controlled by an Oxford Instruments (OI) Mercury iPS magnet controller; a Rohde & Schwarz (R&S) ZVA vector network analyzer (VNA) is used for generating the microwave signal and detecting the complex transmission parameter $S_{21}(f)$. The sweep is realized in Listing 3. Here, both instruments are connected via Ethernet at fixed IP addresses, with the OI Mercury accepting plain TCP connections, and the R&S ZVA using VXI-11 protocol.

Part A of the listing defines and initializes the connected remote-controlled instruments in the same way as already demonstrated in Listing 3. Here, both instruments are connected via Ethernet at fixed IP addresses, with the OI Mercury accepting plain TCP connections, and the R&S ZVA using VXI-11 protocol.

In part B, the two instruments are connected to so-called sweeps. The magnet controller is connected to a continuous magnetic field sweep, which is internally defined by a class Lab::Moose::Continuous::Magnet. Multiple parameters such as start/stop points and the sweep rate are provided to the sweep controller. The sweep controller is then initialized.

Part C of Listing 4 defines the sweeps. The VNA is connected to a stepwise sweep of the output frequency. This way, the complex transmission will be measured at few discrete microwave frequencies; the VNA is doing fast “point measurements”, instead of internally performing a frequency sweep.

Part D defines the measurement subroutine, a callback that is executed for each point in the addressed output parameter space. In this example it reads out the magnetic field as additional column in front. The start method in part E finally starts the measurement.

Listing 3: Accessing a Stanford Research SR830 lock-in amplifier connected via Linux GPIB on the instrument class level: reference signal amplitude and frequency as well as signal amplitude and phase are read out and displayed.

Listing 4: Example measurement script based on the sweep layer. An Oxford Instruments Mercury power supply is performing a continuous magnetic field sweep; in an inner loop, complex signal transmission is measured by a Rohde & Schwarz ZVA vector network analyzer at several discrete frequency values. Data is recorded in Gnuplot format and plotted in real time.
measurement via the outer (magnet) sweep and provides the glue connecting sweeps, data file, and measurement subroutine.

The overall design of the Lab::Measurement code is intended to provide a flexible high-level interface, while requiring only a minimum of programing knowledge for typical measurement tasks. Given their structure, the measurement scripts might even be pregenerated by a graphical user interface, while still allowing a maximum of internal tuning and adaption for the expert. Fig. 2 shows an overview of the classes is the sweep layer and the data logging framework. Data files and live plots are implemented as separate classes, which can also be used independently of the sweep functionality.

5. Quality control

Lab::Measurement is provided with a set of unit tests that can be run upon installation. The unit tests are integrated with the GitHub development repository via Travis [19] (for testing on Linux, under a wide range of Perl 5 versions) and Appveyor [20] (on Microsoft Windows) and run immediately on addition of new code commits. The current test status of the master branch is displayed on the Lab::Measurement homepage. In addition, release test reports on a wide range of software combinations, submitted by volunteers, are available via the CPANTesters website [21].

5.1. Testing with mock connection objects

Comprehensive testing of a large part of the provided functionality is impossible without having the corresponding hardware connected. To extend testing as far as possible, our testing routines simulate instrument responses using mock connection objects as described below.

Listing 5: Example YAML log file for mock connection testing of the SR830 lock-in amplifier driver.

```
---
id: 0
method: Clear
command: '*CLS'
id: 1
method: Write
command: '*RST'
id: 2
method: Write
  timeout: 10
command: SNAP?1,2
id: 3
method: Query
  retval: "0,0\n"
  timeout: 3
---
```

A mock test consists of an ordinary measurement script which interfaces with one or more instruments. To select between logging and mock operation, additional command-line processing code is provided in the MockTest package, which is provided with the tests. The test script is first run connected to a real instrument. Logging of the communication is provided by the instrument layer read, write, and query methods, independent of the specific instrument driver module. Each call to these methods is recorded with its arguments and the resulting return values into a human readable YAML text file, which is then stored alongside with the test script. An example log file for the SR830 lock-in amplifier is shown in Listing 5.

Running a test without the connected instrument will use the Mock connection, which takes such a YAML log file as input. Method calls on the mock connection will be compared with the recorded method calls; deviations from the log will lead to a test failure, allowing to ascertain the impact of committed code on the device communication. In case the test script provides the correct commands, the respective instrument responses are provided from the log file. This framework allows the creation of unit tests with considerably more coverage compared to those distributed in alternative open-source solutions [11,12].

6. Historical interface

Over the past years, Lab::Measurement has undergone several large scale revisions. Development was started in 2006, initially only as a solution for addressing devices via the National Instruments (NI) VISA libraries [22,23] for Linux or MS Windows. The code was later extended and refactored into a layer model, providing the abstractions for connections to instruments and instrument model specific features. The initial high-level interface focused only on logging and plotting, without providing any loop functionalities. Its successor, Lab::XPRESS, was added in 2012 and is with its documentation still present in the distribution for ongoing support of measurement scripts. The intent is to remove this deprecated code when all parts have been fully ported to Moose and Lab::Measurement 4 is released.

The historical stack uses an additional bus layer, in analogy to a GPIB adaptor carrying connections to several instruments. All components are implemented using minimal object-oriented Perl. In the high-level interface, Lab::XPRESS, sweep classes, data logging and plotting are tightly integrated. A main objective of the Moose-based sweep classes was to modularize and simplify this part of the software, in order to allow easier integration of new features.

Aspects that still require porting to the new high-end Moose code include predefined command line switch handling for measurement scripts and customized handling of keyboard interrupts.

7. Requirements and licensing

Lab::Measurement is written in pure Perl and designed to run on any version since Perl 5.14. Given the extensive use of Moose and its object-oriented programming features, a range of Perl module dependencies is required. These, including minimum versions where applicable, are declared in the distribution metadata META.json file included in the package and can be installed automatically by cpan or any Perl package manager.

The package is tested regularly and supported on both Linux and Microsoft Windows; however, given availability of hardware back-ends, should also work on other operating systems. Hardware back-ends may require further dependencies, as, e.g., in the case of Lab::VISA the National Instruments VISA driver stack, or in
the case of USB::TMC the libusb system library. Further details on these requirements can be found in the documentation of the back-end modules on CPAN.

Given that any plotting or graphical interface is optional and that the CPU and memory footprint of running Perl scripts is very low compared to commercial instrument control solutions [1,2]. Lab::Measurement also lends itself for background control operation, logging, and headless server operation. The open source nature of its dependencies particularly on Linux allows the use arbitrary Linux systems, in particular including, e.g., ARM or AArch64 based embedded architectures.

As many other Perl module distributions, Lab::Measurement is released under the same license as Perl itself, meaning dual-licensed either under the Artistic License or the GNU General Public License, version 1 or any later version published by the Free Software Foundation. With this it is free and open source software, and can be downloaded from the Comprehensive Perl Archive Network (CPAN).

8. Summary

Lab::Measurement is a measurement framework designed for high portability and extensibility. The framework is in active use and was applied successfully in many condensed matter physics experiments. Its implementation consists of an object oriented layer structure. The connection layer provides backends for common instrumentation protocols on both Linux and Microsoft Windows. The instrument layer, which represents connected equipment, uses modern object oriented programming techniques for code reuse. A high-level interface, suitable for users without previous Perl experience, allows fast creation of complex measurement tasks involving continuous or discrete sweeps of control parameters as, e.g., voltages, temperature, or magnetic field. By using mock connection objects, unit tests can be run without connected instruments. This allows safe refactoring and facilitates the future evolution of the framework.

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