

Realtime embedded coding in C++ under Linux

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Chapter 1

Introduction

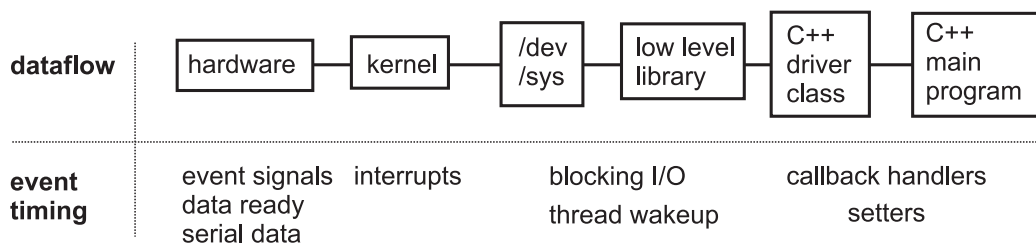


Figure 1.1: Dataflow and timing in low level realtime coding

1.1 Event based coding in the Linux userspace

Realtime embedded coding is all about *events*. These can be a binary signal such as somebody opening a door or an ADC signalling that a sample is ready to be picked up. Fig. 1.1 shows the basic dataflow and how event timing is established: devices by themselves have event signals such as “data ready” or “crash sensor has been triggered”. The Linux kernel receives these as interrupt callbacks. However, userspace has no direct interrupt mechanism; instead it has *blocking I/O* where a read or write operation blocks until a kernel-side interrupt/event has happened. A blocking I/O call returning may then be translated to callbacks between classes by waking up threads. Data is transmitted back to the hardware via methods called “setters”, which change an object’s attributes and potentially do other processing.

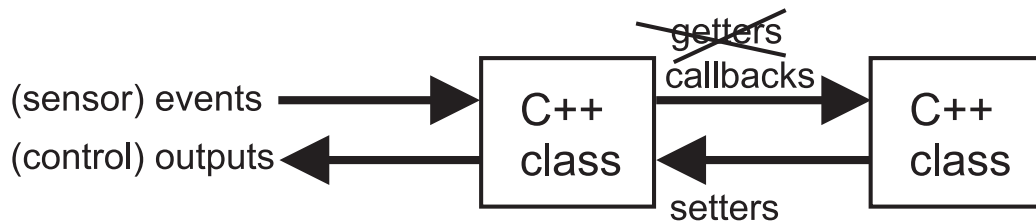


Figure 1.2: A realtime system with two C++ classes. Communication between classes is achieved with callbacks (not getters) for incoming events and setters to send out control events. The control output itself receives its timing from the events so that the loop is traversed as quickly as possible.

Fig. 1.2 shows the overall communication between C++ classes in a realtime system. This communication is done via **callbacks** (*not* getters) and setters, where an event from a sensor traverses according to its realtime requirements through the C++ classes via callbacks and then back to the control output via setters. For example, a collision sensor at a robot triggers a GPIO pin, which then triggers a callback to issue an avoidance action which in turn then sets the motors in reverse.

Callbacks can be seen as userspace interrupt service routines. These must always complete immediately so that the caller does not experience any noticeable delay. For example when a user presses a button in a GUI the callback must be processed without any noticeable delay which is application specific. If processing takes longer then a thread should be started which in turn then will then have a callback signalling success.

In the following sections we are describing how to write event driven code in C++. Important here is

1. blocking I/O and,
2. threads woken up by blocking I/O.

Chapter 2 focuses on how to wrap the low level blocking Linux I/O in a class and how to establish the communication between classes while the chapter 3 describes how threads can effectively be used to trigger callbacks with blocking I/O. Chapter 4 then presents the event based communication in Qt, in particular user interaction and animations. Chapter 6 tackles the same issues as for Qt but for website server communication. The final chapter 7 then describes how events are transmitted back from a C++ class to the user with the help of setters.

Chapter 2

Writing C++ classes for userspace event processing

This chapter focuses on writing your own C++ class for event processing by hiding away the complexity (and messy) low level C APIs and/or raw device access. How are events translated into I/O operations? On the hardware-side we have event signals such as data-ready signals or by the timing of a serial or audio interface. The Linux kernel translates this timing info into blocking I/O on the pseudo filesystem `/dev` which means that a read operation blocks until data has arrived or an event has happened. The task of a C++ programmer is to hide this complexity and these quite different approaches in C++ classes which communicate via callbacks and setters with the client classes.

2.1 General recommendations on how to write C++ event processing classes

As said above the main purpose of object oriented coding here is to hide away the complexity of low level driver access and offer the client a simple and safe way of connecting to the sensor. In particular:

1. Setters and callbacks hand over *physical units* (temperature, acceleration, ...) or relative units but not raw integer values with no meaning.
2. The sensor is configured by specifying physical units (time, voltage, temperature) and not sensor registers. Default config parameters should be specified that the class can be used straight away with default parameters.

3. In the build system bundle classes into separate libraries so that they can be re-used easily.
4. The class comes with simple demo programs demonstrating how a client program might use it.

2.2 Callbacks between C++ classes

Events between C++ classes are transmitted via callbacks. There are different ways of tackling the issue of callbacks but the most effective way is defining a method in an *interface class* as *abstract* and asking the client class to implement it in a derived class.

The callback is part of an interface class:

```
struct ADSCallbackInterface {  
    /**  
     * Called when a new sample is available.  
     * This needs to be implemented in a derived  
     * class by the client. Defined as abstract.  
     * \param sample Voltage from the selected channel.  
     */  
    virtual void hasADS1115Sample(float sample) = 0;  
};
```

and then registering it in the main device driver class:

```
void registerCallback(ADSCallbackInterface* ci) {  
    adsCallbackInterfaces.push_back(ci);  
}
```

where `adsCallbackInterfaces` is a `std::vector` of containing instances of `ADSCallbackInterface`.

This then allows the C++ class to transmit an event to the receiving classes by looping through the interface pointers:

```
for(auto &cb: adsCallbackInterfaces) {  
    cb->hasADS1115Sample(v);  
}
```


See https://github.com/berndporr/rpi_ads1115 for a complete example.

Note that an interface can also be defined by `std::function` but this is a lot slower than using interfaces. The reason is that interfaces are standard C++ and the compiler can optimise these constructs while `std::function` does a lot of trickery behind the scenes which a compiler won't understand and thus won't be able to optimise. The other reason why `std::function` is discouraged is the difficulty to provide proper documentation for the function arguments and return values.

2.2.1 Callback arguments

Above the callbacks just delivered one floating point value. However, often more than one sample or more complex data are transmitted:

- Complex data: do not put loads of arguments into the callback but define a *struct*. For example an ADC might deliver all 4 channels at once:

```
class ADmulti {  
  
    struct ADCSample {  
        float ch1;  
        float ch2;  
        float ch3;  
        float ch4;  
    };  
  
    ...  
    virtual void hasSample(ADCSample& sample) = 0;  
    ...  
};
```

Depending on your application, you might consider the values not useful individually and therefore prefer a `std::tuple`.

- Arrays: Use arrays which contain the length of the arrays: either `std::array`, `std::vector`, etc or const arrays and then references to these so that the callback knows the length. For example the LIDAR callback uses a reference to a const length array:

```

/**
 * Callback interface which needs to be implemented by the user.
 */
struct DataInterface {
    virtual void newScanAvail(
        float rpm,
        A1LidarData (&)[A1Lidar::nDistance]) = 0;
};

```

Here `A1Lidar::nDistance` is a constant-expression giving the fixed array length, and `(&)[A1Lidar::nDistance]` a reference to a constant-length array which containing `A1LidarData` structs. If you're going to use types that hard to key-in often, typedef them.

In terms of *memory management*:

1. Low sampling rate complex data structures: allocate as a local variable. It can be a simple type or a struct. See `dataReady()` in: https://github.com/berndporr/LSM9DS1_RaspberryPi_CPP_Library/blob/master/LSM9DS1.cpp.
2. High sampling rate buffers: allocate memory on the heap in the constructor or in the private section of the class as a const length array and pass on a *reference*. See `getData()` in https://github.com/berndporr/rplidar_rpi.

2.3 Low level userspace device access

The following sections provide pointers of how to write the C++ driver classes for different hardware protocols which then emit events via callback interfaces.

To emulate an “interrupt” or event in userspace we need blocking I/O which provides the timing for example when waiting for a GPIO change, doing audio or video I/O.

Generally any userspace program talks to the kernel via pseudo files in the `/dev` or `/sys` directories.

2.3.1 Video camera capture (openCV)

Ubuntu / Debian Linux systems

Reading from a video camera is usually done with the help of openCV which in turn then talks to the low level C API which in turn talks to the kernel via `/dev/video*`.

```
while(running) {  
    cv::Mat cap;  
    videoCapture.read(cap);  
    sceneCallback->nextScene(cap);  
}
```

The `read(cap)` command is blocking till a new frame has arrived which is then transmitted with the callback `nextScene` to the client. The full code of the example camera class is here: <https://github.com/berndporr/opencv-camera-callback>.

Raspberry PI

On the raspberry PI a new video stack has been implemented which talks to the kernel via `/dev/media*`. This is incompatible with openCV and the code in section 2.3.1 won't work. The good news is that `libcamera` already implements a callback. Instead, one just needs to register a callback to receive the video frames. The bad news is that `libcamera` is highly complex and requires a lot of additional code (<https://github.com/libcamera-org/libcamera/blob/master/Documentation/guides/application-developer.rst>). To make life easier we have written a C++ wrapper around the `libcamera` C++ API which exposes a callback which delivers image frames in openCV format to mimick the behaviour of the openCV code of the previous section 2.3.1: <https://github.com/berndporr/libcamera2opencv>.

2.3.2 Audio (ALSA)

The standard framework for audio is `alsa`: <https://github.com/alsa-project>.

ALSA is packet based with a `read` command returning a chunk ("buffer") of audio and `write` emitting one. There are calls to set the sample format, sample rate, buffer size and so forth.

First, the parameters are requested and the driver can modify or reject them:

```

/* Signed 16-bit little-endian format */
snd_pcm_hw_params_set_format(handle, params,
                             SND_PCM_FORMAT_S16_LE);

/* One channel (mono) */
snd_pcm_hw_params_set_channels(handle, params, 1);

/* 44100 bits/second sampling rate (CD quality) */
val = 44100;
snd_pcm_hw_params_set_rate_near(handle, params,
                                 &val, &dir);

```

Then playing sound is done in an endless loop where a `read()` or `write()` command is issued. Both are blocking so that they guarantee event timing of audio both ways.

```

while (running) {
    if ((err = snd_pcm_readi(handle, buffer, buffer_frames)) != buffer_frames) {
        if (errCallback) errCallback->hasError();
    }
    if (sampleCallback) sampleCallback->hasData(buffer);
}

```

For a full coding example “`aplay`” and “`arecord`” are a good start. Both can be found here: <https://github.com/alsa-project>.

2.3.3 Bluetooth

Bluetooth has also blocking I/O so that one can wait for incoming packets on a socket:

```

void run() {
    doRun = 1;
    while (doRun) {
        recv(btsocket, recvbuffer, sizeof(recvbuffer), 0);
        hasData(recvbuffer);
    }
};

```

Here the `recv` command blocks until new data has arrived.

2.3.4 General purpose I/O (GPIO)

GPIO pins are not just simple digital ports but they can be used to turn non-blocking I/O into blocking I/O, or in other words: events! SPI and I2C are only blocking for their read/write operations but they don't know when new data is available at a sensor so one needs to connect the DATA-READY output of a sensor to a GPIO port which then feeds into blocking I/O.

libgpiod

The GPIO (of the raspberry PI) can easily be controlled via the `/dev` filesystem and `libgpiod`.

Use the commandline tool `gpioinfo` to print a list of all available GPIO pins. When you use the `gpiod` library you:

1. first choose the GPIO *chip* you want to use. Raspberry PIs 1-4 have only one chip. The Raspberry PI 5 has 4 chips. Selection can be made either by number, name or pseudo-file:

```
struct gpiod_chip *chip =  
    gpiod_chip_open_by_name("gpiochip0");
```

and then,

2. select a pin on the chip:

```
struct gpiod_line *pinRed =  
    gpiod_chip_get_line(chip, 24);
```

Output

Once you have a pointer to the pin you can then set its direction, for example as an output pin, with:

```
gpiod_line_request_output(pinRed, "example1", 0);
```

and set its value with:

```
gpiod_line_set_value(pinRed, 1);
```

Events

libgpiod offers all the functionality of event processing via blocking I/O! Here, change in level from low to high or high to low unblocks an I/O operation, awakening its underlying thread which then one can perform a callback.

To request event processing on a pin simply requires this single command:

```
int ret =  
    gpiod_line_request_rising_edge_events(pinSwitch, "Consumer1");
```

This will turn the GPIO pin `pinSwitch` into an input pin and enable blocking I/O on this pin.

Then start a thread where its worker contains:

```
void worker() {  
    while (running) {  
        constexpr struct timespec ts = { 1, 0 };  
        gpiod_line_event_wait(pinSwitch, &ts);  
        struct gpiod_line_event event;  
        gpiod_line_event_read(pinSwitch, &event);  
        event_callback();  
    }  
}
```

The `gpiod_line_event_wait` waits for a rising edge at the GPIO pin, or for 1 second (+ 0ns), whichever is longer, and then unblocks. The return value is 1 if a GPIO event occurred, 0 if timeout interval was exceeded, and -1 in the event of an error. In production code, you'd need to check this return value. Then `gpiod_line_event_read` transfers the kernel event to userspace and clears it out of the kernel event queue. It's important to do the read operation even if the event-struct is never used. The callback is made, and the loop repeats until another thread requests termination by setting `running` to false. See https://github.com/berndporr/libgpiod_event_demo for a complete example.

Releasing the GPIO

Once you are finished, release the GPIO pin with:

```
gpiod_line_release(pinRed);
```

and close the chip:

```
gpiod_chip_close(chip);
```

2.3.5 SPI

Table 2.1: SPI modes

SPI Mode	CPOL	CPHA	Idle state
0	0	0	L
1	0	1	L
2	1	1	H
3	1	0	H

SPI is a protocol which usually transmits and receives at the same time. Its calls are blocking for the duration of receive and transmit but cannot be used for event based processing. If an SPI device is used events should be transmitted via an additional GPIO line. Even though data might not be used it needs to be matched up, because the same clock is used to send and collect the data signal (it is *isochronous*). So if you send 8 bytes the hardware receives 8 bytes at the same time.

Transfer to/from SPI is best managed by the low level access to `/dev`. Open the SPI device with the standard `open()` function:

```
int fd = open( "/dev/spidev0.0", O_RDWR);
```

Then set the SPI mode (see table 2.1):

```
int ret = ioctl(fd, SPI_IOC_WR_MODE, &mode);
```

as explained, for example, here: <https://www.analog.com/en/analog-dialogue/articles/introduction-to-spi-interface.html>.

Because SPI is isochronous, `read()` and `write()` can't be used to transmit and receive data. Instead, the simultaneous read and write is performed using an `ioctl()` to do the communication. Populate this struct:

```
struct spi_ioc_transfer tr {  
    .tx_buf = (unsigned long)tx1,
```

```

    .rx_buf = (unsigned long)rx1,
    .len = ARRAY_SIZE(tx1),
    .delay_usecs = delay,
    .speed_hz = speed,
    .bits_per_word = 8,
};

```

which points to two character buffers “tx” and “rx” with the same length¹.

Reading and simultaneous writing then happens via this `ioctl()` function call:

```
int ret = ioctl(fd, SPI_IOC_MESSAGE(1), &tr);
```

Sometimes the SPI protocol of a chip is so odd that even the raw I/O via `/dev` won’t work and you need to write your own bit banging interface, for example done here for the ADC on the alphabot: <https://github.com/berndporr/alphabot/blob/main/alphabot.cpp#L58>. This is obviously far from ideal as it might require `usleep()` commands so that acquisition needs to be run in a separate thread (the alphabot indeed uses a timer callback in a separate thread).

Overall the SPI protocol is often device dependent and calls for experimentation to get it to work. On some ADCs the SPI clock is also the conversion clock and a longer lasting clock signal sequence is required, making it necessary to transmit dummy bytes in addition to the payload.

As a general recommendation do not use SAR converters which use the SPI data clock also as acquisition clock as they are often not compatible with the standard SPI transfers via `/dev`. Use sensors or ADCs which have their own clock signal.

2.3.6 I2C

I2C is a protocol which either receives or transmits. Its I/O operations are blocking but only for the duration of receive or transmit. Use an additional GPIO pin for events for example for a data-ready event.

The I2C bus has two signal lines (SDA & SDL) which must be pulled up by resistors. Every I2C device has an address on the bus. You can scan a bus with **i2cdetect** (part of the `i2c-tools` package):

¹This code fragment’s use of designated initialisers officially requires C++2a, although most C++ compilers support it when compiling with older standards. In C it’s been fine for a while!


```

root@raspberrypi:/home/pi# i2cdetect -y 1
    0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f
00:                -- -- -- -- -- -- --
10: -- -- -- -- -- -- -- -- -- -- -- 1e --
20: -- -- -- -- -- -- -- -- -- -- -- -- --
30: -- -- -- -- -- -- -- -- -- -- -- -- --
40: -- -- -- -- -- -- -- -- -- -- -- -- --
50: -- -- -- -- -- -- -- -- 58 -- -- -- -- --
60: -- -- -- -- -- -- -- -- -- -- 6b -- -- --
70: -- -- -- -- -- -- -- -- -- -- -- -- --
root@raspberrypi:/home/pi#

```

In this case there are 3 I2C devices on the I2C bus at addresses 1E, 58 and 6B and need to be specified when accessing the I2C device.

Raw /dev/i2c access

I2C either transmits or receives but never at the same time so here we can use the standard C read/write commands. However, we need to use ioctl to tell the kernel the I2C address:

```

char buf[2];
int file = open("/dev/i2c-2",O_RDWR);
int addr = 0x58;
ioctl(file, I2C_SLAVE, addr);
write(file, buf, 1)
read(file, buf, 2)

```

where addr is the I2C address. Then use standard read() or write() commands. Usually the 1st write operation tells the chip which register to read or write to. Subsequent operations read or write that register. For example, reading a 16 bit register:

```

unsigned 2c_readWord(uint8_t reg)
{
uint8_t tmp[2];
tmp[0] = reg;
write(fd_i2c,&tmp,1);
    read(fd_i2c, tmp, 2);
}

```

```

        return (((unsigned)(tmp[0])) << 8) | ((unsigned)(tmp[1]));
    }

```

Similarly writing a 16 bit register writes 3 bytes to the I2C bus (register and the 16 bit data):

```

void i2c_writeWord(uint8_t reg, unsigned data)
{
    uint8_t tmp[3];
    tmp[0] = reg;
    tmp[1] = (char)((data & 0xff00) >> 8);
    tmp[2] = (char)(data & 0x00ff);
    write(fd_i2c,&tmp,3);
}

```

2.3.7 Access to hardware via special devices in /sys

Some sensors are directly available via the sys filesystem in human readable format. For example

```
cat /sys/class/thermal/thermal_zone0/temp
```

gives you the temperature of the CPU.

2.3.8 Accessing physical memory locations (danger!)

Don't. In case you really need to access registers you can also access memory directly. This should only be used as a last resort. For example, setting the clock for the AD converter requires turning a GPIO pin into a clock output pin. This is not yet supported by the drivers so we need to program registers on the RPI.

- Linux uses virtual addresses so that a pointer won't point to a physical memory location. It points to three page tables with an offset.
- Special device `/dev/mem` allows access to physical memory.
- The command **mmap** provides a pointer to a physical address by opening `/dev/mem`.
- Example:

```

int *addr;
if ((fd = open("/dev/mem", O_RDWR|O_SYNC)) < 0 ) {
    printf("Error opening file. \n");
    close(fd);
    return (-1);
}
addr = (int *)mmap(0, num*STRUCT_PAGE_SIZE, PROT_READ, MAP_PRIVATE,
                  fd, 0x0000620000000000);
printf("addr: %p \n",addr);
printf("addr: %d \n",*addr);

```

- Use this with care! It's dangerous if not used properly.

2.4 Kernel driver programming

You can also create your own `/dev/mydevice` in the `/dev` filesystem by writing a kernel driver and a matching userspace library. For example the USB mouse has a driver in kernel space and translates the raw data from the mouse into coordinates. However, this is beyond the scope of this handout. If you want to embark on this adventure then the best approach is to find a kernel driver which does approximately what you want and modify it for your purposes.

2.5 Conclusion

The communication between C++ classes is achieved via callbacks and setters. The event from the sensor traverses the C++ classes via callbacks and then back to the control output via setters.

From the sections above it's clear that Linux user-space low level device access is complex, even without taking into account the complexity of contemporary chips which have often a multitude of registers and pages of documentation. Your task is to hide away all this (scary) complexity in a C++ class and offer the client an easy-to-understand interface.

Chapter 3

Threads

3.1 Introduction

In realtime systems threads have two distinct functions:

1. Loops with blocking I/O to establish **precise timing** for callbacks.
2. **Asynchronous execution** of time-consuming tasks with a callback after the task has completed.

3.2 Processes and Threads

Processes are different programs which seem to be running at the same time. A small embedded system may only have a single CPU core, so this is achieved by the operating system switching approximately every 10ms from one process to the next so it feels as if they are running concurrently. A thread is a lightweight process. A process may have multiple threads which share the same address-space and are all started from within the parent process. As with processes, the threads seem to be running at the same time. When a thread is started it runs simultaneously with the main process which created it.

3.3 Thread and worker

A thread is just a *wrapper* for the actual method which is running independently. The method being run in the thread is often called a *worker*.

3.3.1 Creating threads

In C++ a worker is a method within a class:

```
uthread = std::thread(&MyClassWithAThread::run, this);
```

where `MyClassWithAThread` is a class containing the function “run”:

```
class MyClassWithAThread {
    void run() {
        // ... hard work is done here
        doCallback(result); // hand the result over
    }
}
```

Note that the `&` signifies a functor, a method prototype. Instead of using functors you can also use a lambda function to call a method in the instance:

```
uthread = std::thread([this]() {run();});
```

3.3.2 Lifetime of a thread

Threads terminate simply once the worker has finished its job. To tell the client that a thread has finished you can use a *callback* to trigger an event.

Sometimes it’s important to wait for the termination of the thread, for example when your whole program is terminating or when you stop an endless loop in a thread. To wait for the termination of the thread use the “`join()`” method:

```
void stop() {
    uthread.join();
}
```

In a realtime system `join` is most likely only needed when shutting down the program.

3.3.3 Running/stopping workers with endless loops

Threads with endless loops are often used in conjunction with blocking I/O which provide the timing:

```

void run() {
    running = true;
    while (running) {
        read(buffer); // blocking
        doCallback(buffer); // hand data to client
    }
}

```

Note the flag `running` which is controlled by the main program and is set to zero to terminate the thread:

```

void stop() {
    running = false; // <----- HERE!!
    uthread.join();
}

```

Note that `join()` is a blocking operation and needs to be used with care not to lock up the main program. You probably only need it when your program is terminating. See https://github.com/berndporr/rpi_AD7705_daq for an example.

If your program creates and joins several threads while executing, with care you might be able to design your program to allow an end-of-life thread to carry on tidying up in the background after you stop it by setting `running = false`. In this case only need execute `join()` to be sure that the thread has finished. Joining a terminated thread is OK (the call just returns immediately) but you absolutely must not join a thread more than once, nor delete a thread until you've joined it.

3.3.4 Timing within threads

Threads are perfect to create timing without using `sleep` commands with the help of *blocking I/O*. Blocking I/O puts a thread to sleep and is woken up after new data has arrived or has been written to a device. Blocking I/O won't consume any CPU power and is perfect to tell the kernel that it can execute other threads in the meantime.

Timing with blocking I/O

Blocking I/O (read, write, etc) *is by far the best approach* to time the data coming in because the thread goes to sleep when it's waiting for I/O but wakes

up very quickly after new data has arrived.

In this example the blocking read command creates the timing of the callback:

```
void run() {
    running = 1;
    while (running) {
        read(buffer); // blocking
        doCallback(buffer); // hand data to client
    }
}
```

If the I/O is non-blocking or if you are making blocking I/O non-blocking with:

```
int flags = fcntl(fd, F_GETFL, 0);
fcntl(fd, F_SETFL, flags | O_NONBLOCK);
```

you can then use `select()` which blocks on the file descriptor:

```
FD_ZERO(&rdset);
FD_SET(fd,&rdset);
struct timeval timeout;
timeout.tv_sec = 0;
timeout.tv_usec = 500000;
int ret = select(fd+1,&rdset,NULL,NULL,&timeout);
if (ret < 0) return ret;
// non-blocking I/O read
ret = read(fd,buffer,bytes_per_sample * n_chan);
```

which has the advantage that it has a timeout so that you can create both error and data callbacks. Even if the I/O is blocking using `select` or `poll` has the advantage that these commands have timeouts while the `read` and `write` commands would block forever. This is also the recommended approach for `libgpod` where the `gpod_line_event_wait` is not needed because `gpod_line_event_read` is blocking but would block indefinitely.

3.4 Timing with Linux timers

If no timing info from the sensor is available one can use a timer as a last resort. Under Linux reliable timing can be again created with the help of blocking I/O

and threads. Here, a special file descriptor receives information when a timer has fired first and at which intervals after:

```
fd = timerfd_create(CLOCK_MONOTONIC, 0);
its.it_value.tv_sec = millisecs / 1000;
its.it_value.tv_nsec = (millisecs % 1000) * 1000000;
its.it_interval.tv_sec = millisecs / 1000;
its.it_interval.tv_nsec = (millisecs % 1000) * 1000000;
if (timerfd_settime(fd, 0, &its, NULL) == -1)
    throw("Could not start timer");
```

This file descriptor is then used in a loop with a blocking read command which then wakes up at the specified intervals:

```
running = true;
while (running) {
    uint64_t exp;
    read(fd, &exp, sizeof(uint64_t));
    timerEvent();
}
```

where `timerEvent` is as usual the callback which is called at the specified intervals.

However, generally it's *not recommended* to use timers for anything which needs to be sampled at high temporal precision, for example ADC converters or sensors with sampling rates higher than a few Hz.

3.5 Conclusion

Threads play a central role in real-time coding as, together with blocking I/O, they establish the callback interfaces. Every event handler runs in a separate thread.

Callbacks are also used to signal the termination of threads, which shows again the close relationship between threads and callbacks.

Chapter 4

Realtime/event processing within the Graphical User Interface Qt

4.1 Introduction

Qt is a cross-platform windows development environment for Linux, Windows and Mac. Such graphical user interfaces have realtime requirements because, for example, pressing a button should trigger an instant response by the application so that the user thinks this has been instantaneous. QT also works with callbacks as introduced above but they are wrapped in a QT-specific signal/slot concept.

Elements in Qt are *Widgets* which can contain anything from plots, buttons or text fields. They are classes. You can define your own widgets or use ready-made ones. Realtime communication within QT happens between widgets where then one widget calls another widget, for example a button that calls the main window if a button press has happened.

The arrangements of widgets on the screen is managed by layouts. There are different ways of declaring layout in Qt. One is using a markup language which then has matching classes; another is creating to use only C++ classes. We show how to organise the layout using the second method. This avoids having to learn an additional language and is consistent with the general trend to use code to declare the layout in this and other frameworks (**SwiftUI**, for example).

This is an example how widgets are organised into nested vertical and horizontal layouts (see Fig. 4.1 for the result).

```
// create 3 widgets
button = new QPushButton;
```

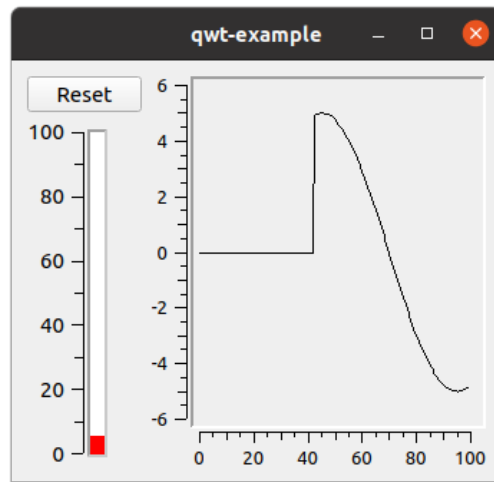


Figure 4.1: QT example layout

```
thermo = new QwtThermo;  
plot = new QwtPlot;  
  
// vertical layout  
vLayout = new QVBoxLayout;  
vLayout->addWidget(button);  
vLayout->addWidget(thermo);  
  
// horizontal layout  
hLayout = new QHBoxLayout;  
hLayout->addLayout(vLayout);  
hLayout->addWidget(plot);  
  
// main layout  
setLayout(hLayout);
```

4.2 Callbacks in Qt

4.2.1 Events from widgets

In contrast to our low level callback mechanism using interfaces, Qt rather directly calls methods in classes. The problem is that function pointers cannot be directly used as a class has instance pointers to its local data. So a method of a class needs to be combined with the instance pointer. The Qt method “connect” does exactly that:

```
connect(button, &QPushButton::clicked,  
        this, &Window::reset);
```

The QPushButton instance `button` has a method called `clicked()` which is called whenever the user clicks on the button. This is then forwarded to the method `reset()` in the application `Widget`.

4.2.2 Plotting realtime data arriving via a callback

The general idea is to store the real-time samples from a callback in a buffer and trigger a screen refresh at a lower rate. For example, we may choose to replot the samples in the buffer every 40 ms because that fast enough for the user, whereas plotting the whole buffer every sample would be too CPU-intensive.

A callback `addSample()` is called in real-time whenever a sample has arrived:

```
void Window::addSample( float v ) {  
    // add the new input to the plot  
    std::move( yData, yData + plotDataSize - 1, yData+1 );  
    yData[0] = v;  
}
```

which stores the sample `v` in the shift buffer `yData`.

Then the screen refresh (which is slow) is done at a lower and unreliable rate:

```
void Window::timerEvent( QTimerEvent * )  
{  
    curve->setSamples(xData, yData, plotDataSize);  
    plot->replot();  
    thermo->setValue( yData[0] );  
    update();  
}
```

`update()` in the timer event-handler generates a paint event and Qt then invokes the repaint handler “as soon as possible” (which is to say, not in real-time) to repaint the canvas of the widget:

```
void ScopeWindow::paintEvent(QPaintEvent *) {  
    QPainter paint( this );  
  
    paint.drawLine( ... )  
}
```

Note that neither the timer nor the `update()` function is called in a reliable way but whenever Qt chooses to do it. So Qt timers cannot be used to sample data but should only be used for screen refresh and other non-time-critical reasons.

4.3 Conclusion

Events in Qt are generated by user interaction, for example a button press or moving the mouse. As before Qt provides a callback mechanism via the `connect()` method. Callbacks from Qt timers may be used for animations but must not be used for real-time events as Qt timers won't guarantee a reliable timing.

Chapter 5

Realtime publisher-subscriber communication with DDS

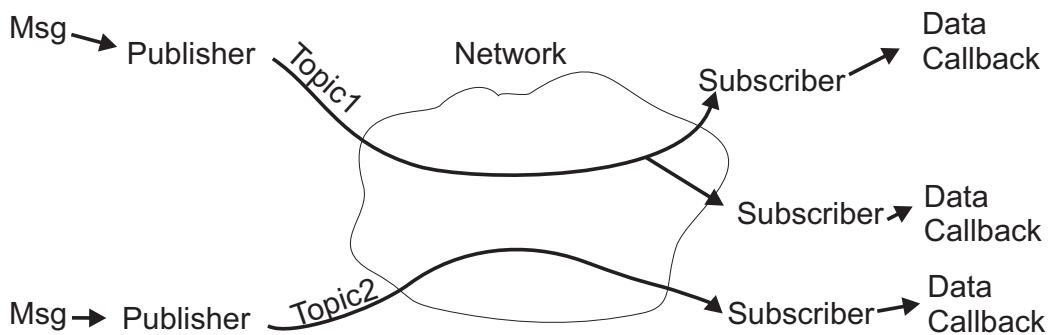


Figure 5.1: FastDDS.

So far communication has only been between classes within the same program on the same computer. However, often data needs to be transmitted in realtime over a network. The Data Distribution Service (DDS) is a middleware protocol and API which has been developed to provide reliable and low-latency publisher-subscriber communication (see Fig. 5.1): a publisher sends a message (here a C++ struct) through a communication channel which is called a “topic”. The subscriber receives messages from all the topics to which it has subscribed, and then triggers callbacks delivering those messages. We focus on fastDDS which uses the RTPS (Real Time Publish Subscribe) protocol. It offers plug and play connectivity which won’t require to specify IP addresses in a local networks so

that applications are automatically discovered. fastDDS is now the standard middleware of ROS2, the popular robotic operating system.

Here are the steps how to use fastDDS. A complete demo application is here: https://github.com/berndporr/fastdds_demo.

5.1 Essential classes and their rôles

Domain refers to a collection of actors which publish and/or subscribe to topics.

DomainParticipant is a factory class for publishers, subscribers and topics.

Topic means a category of messages passed between actors in the domain. It's the method by which a participant which receives messages may filter output only those that are relevant.

Publisher participants send messages to every other participant which is listening for information on a given topic.

Subscriber participants receive messages on the topic(s) wo whcih they have subscribed.

5.2 Define the data structure

The idea with fastDDS is to specify a data structure as a C++ style struct which is then converted into header and cpp files. For example the template HelloWorldMsg.idl:

```
struct HelloWorldMsg
{
    unsigned long index;
    string message;
};
```

contains an unsigned long int and a C++ string. This template file is then converted to C++ header and cpp files with the helper:

```
fastddsgen HelloWorldMsg.idl
```

which of course should be automated by your cmake build system.

5.3 Publisher

The Publisher wants to be able to send messages to every object that is subscribed to its topic. It has to do three things to achieve this:

1. Create a topic to which interested objects can subscribe;
2. Create a Publisher which is a factory class to create any required writers, callback handlers etc.; and
3. Use that Publisher to create a DataWriter that actually sends messages on a particular topic.

5.3.1 Creating a Topic

`Participant.create_topic` is used to associate the topic with the data structure which will be passed to that topic's subscribers. The example program calls it like this:

```
topic_ = participant_->create_topic("HelloWorldTopic",  
                                   "HelloWorldMsg",  
                                   TOPIC_QOS_DEFAULT);
```

5.3.2 Creating a Publisher and a Writer

Message senders and receivers are created by a factory class, Publisher. An instance of this class is required before any writers can be created. The Participant can build Publishers for us using its `create_datawriter` method. In the example program, it looks like this:

```
publisher_ = participant_->create_publisher(PUBLISHER_QOS_DEFAULT,  
                                           nullptr);
```

and with that Publisher, we can create a DataWriter

```
writer_ = publisher_->create_datawriter(topic_,  
                                       DATAWRITER_QOS_DEFAULT,  
                                       &listener_);
```

5.3.3 Specifying the Writer's callback function

`listener_`, the third argument to the `create_datawriter` method above, is an object implementing the callback interface specified by the `DataWriterListener` class, specifically, the `on_publication_matched` method. In the example, the private class `PubListener` provides this functionality. When a subscriber registers to receive messages on the topic, this is the object which will be informed. As this is a minimalistic example, all that `listener_` does is to maintain a thread-safe ("atomic") integer which counts the number of subscribers as they connect and disconnect, and prints messages to the console as they do so. Refer to the [source code](#) in the example to see how it works.

5.3.4 Sending messages

Having packaged this all in a class we can finally implement the method which publishes a message. The code in the example sends the `HelloWorldMsg` referenced by `hello` if any listeners are subscribed. If there is none, it immediately returns false; otherwise it sends the message then returns true.

```
class HelloWorldPublisher
{
    // ... the initialisation described above ... then

    //!Send a publication
    bool publish(HelloWorldMsg& hello)
    {
        if (listener_.matched_ > 0)
        {
            writer_->write(&hello);
            return true;
        }
        return false;
    }
}
```


5.4 Subscriber

The program which wants to receive data on a particular topic needs to subscribe to that topic. The process of creating a subscriber is similar to creating a publisher.:

1. Create the participant that will interact with the topic;
2. Register the data type which the topic uses for its messages;
3. Ask the participant to create a subscriber to that topic;
4. Register the callback by creating a `DataReader` which implements the `DataReaderListener` interface.

5.4.1 Implementation

The relevant code from the example which sets up the infrastructure reads very similarly to the publisher, except that of course the participant is used to create subscriber rather than a writer:

```
topic_ = participant_->create_topic("HelloWorldTopic",
                                   "HelloWorldMsg",
                                   TOPIC_QOS_DEFAULT);
subscriber_ = participant_->create_subscriber(SUBSCRIBER_QOS_DEFAULT,
                                              nullptr);
reader_ = subscriber_->create_datareader(topic_,
                                         DATAREADER_QOS_DEFAULT,
                                         &listener_);
```

5.4.2 Receiving data

`listener_` in the publishing application was a callback object which was called whenever a subscriber joined or left the topic. In the subscribing application it is a callback object which receives data on the topic from a writer whenever any becomes available. It does this by having its `on_data_available` method called. This method will invoke the Reader's `take_next_sample` method to acquire the incoming message data and information, and processes it however the receiving program requires. In the example we just print it out.

```

class SubListener : public DataReaderListener {
public:
    // callback
    void on_data_available(DataReader* reader) override {
        SampleInfo info;
        HelloWorldMsg hello;
        if (reader->take_next_sample(&hello, &info) == ReturnCode_t::RETCODE_OK) {
            if (info.valid_data) {
                std::cout << "Message: " << hello.message()
                    << " with index: " << hello.index()
                    << " RECEIVED." << std::endl;
            }
        }
    }
}

```

Chapter 6

Realtime web server/client communication

6.1 Introduction

There is a wide diversity of Web server / client applications ranging from shopping baskets on vendor sites to social media.

Generally it's easy to create dynamic content (see PHP or nodejs) and this is well documented. However, feeding realtime data from C++ to a web page or realtime button presses back to C++ is a bit more difficult.

It's important to recognise where *events* are generated: it is always the client (web browser or mobile app) which triggers an event, be it sending data over to the server or requesting data. It's always initiated by the client.

6.2 REST

The interface between a web client (browser or phone app) is usually implemented as a Representational State Transfer Architectural (REST) API by communicating via an URL on a web server. The requirements for this API are very general and won't define the actual data format:

Uniform interface. Any device connecting to the URL should get the same reply. No matter if a web page or mobile phone requests the temperature of a sensor the returned format must always be the same.

Client-server decoupling. The only information the client needs to know is the URL of the server to request data or send data.

Statelessness. Each request needs to include all the information necessary and must not depend on previous requests. For example a request to a buffer must not alter the buffer but just read from it so that another user reading the buffer shortly after receives the same data.

See <https://www.ibm.com/cloud/learn/rest-apis> for the complete list of REST design principles.

6.3 Data format: JSON

The most popular dataformat is JSON (`application/json`) which is basically a map of (nestable) key/value pairs:

```
{
  temperature: [20, 21, 20, 19, 17],
  steps: 100,
  comment: "all good!"
}
```

Since JSON is human-readable text a web server can simply generate that text send it over via http or https. There is no difference except that the MIME format is 'application/json' instead of html.

6.4 Server

On the Linux system a web server needs to be set up. There are a variety of different options available but we are focusing here on the ones which can be used for C++ communication (i.e. CGI).

6.4.1 Web servers (http/https)

- NGINX: Easy to configure but very flexible web server. Pronounced “Engine-X”.
- Apache: Hard to configure but safe option

- `lighttpd`: Smaller web server with a small memory footprint. Pronounced “lighty”.

Note that it’s possible to run different web servers at the same time where they then act as proxies for a central web server visible to the outside world. In particular `nginx` makes it very easy to achieve this.

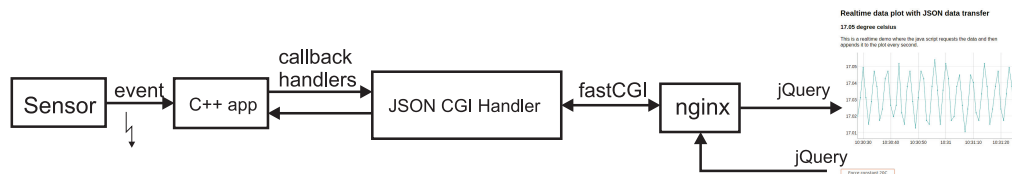


Figure 6.1: FastCGI dataflow.

6.4.2 FastCGI

FastCGI (see Fig 6.1) is written in C++ and generates the entire content of the http/https request. In particular here we generate JSON packets which can then be processed by client JavaScripts and vice versa. For realtime applications JSON transmission is perfect because the client-side JavaScript can request and receive JSON packages

A fast CGI program is a UNIX commandline program which communicates with the web server (`nginx`, `Apache`, ...) via a UNIX socket which in turn is a pseudo file located in a temporary directory for example `/tmp/sensorsocket`.

The web server then maps certain http/https requests to this socket. An example configuration for `nginx` looks like this:

```

location /sensor/ {
    include      fastcgi_params;
    fastcgi_pass unix:/tmp/sensorsocket;
}
  
```

If the user does a request via the URL `www.mywebpage.com/sensor/` then `nginx` contacts the `fastcgi` program via this socket. The `fastcgi` program then needs to return the content. Internally this will be a C++ callback inside of the `fastcgi` program.

The C++ fastcgi API https://github.com/berndporr/fastcgi_json_cpp_api is wrapper around the quite cryptic fastcgi C library and we discuss its callback handlers now.

6.4.3 Server → client

The fastCGI callback expects a JSON string (application/json) with the data transmitted from the server to the client. Use the jsoncpp library (standard debian/Ubuntu package) to create JSON.

```
class JSONcallback : public JSONCGIHandler::GETCallback {
public:
    /**
     * Gets the data and sends it to the webserver.
     * The callback creates two JSON entries. One with the
     * timestamp and an array of sensor readings.
     */
    virtual std::string getJSONString() {
        Json::Value root;
        root["epoch"] = (long)time(NULL);
        Json::Value values;
        for(int i = 0; i < datasink->values.size(); i++) {
            values[i] = datasink->values[i];
        }
        root["values"] = values;
        Json::StreamWriterBuilder builder;
        const std::string json_file = Json::writeString(builder, root);
        return json_file;
    };
};
```

6.4.4 Client → server: POST

Like in any GUI the client can press a button and create an event. Here, the server then receives the JSON data as a callback called “postArg”:

```
virtual void postString(std::string postArg) {
    const auto rawJsonLength = static_cast<int>(postArg.length());
    JSONCPP_STRING err;
```

```

    Json::Value root;
    Json::CharReaderBuilder builder;
    const std::unique_ptr<Json::CharReader> reader(builder.newCharReader());
    reader->parse(postArg.c_str(), postArg.c_str() + rawJsonLength, &root, &err)
    // do something with root
}

```

where root is a std::map.

6.5 Client code: javascript for websites

Generally on the client side (= web page), HTML with embedded *JavaScript* is used to generate realtime output/input without reloading the page. JavaScript is *event driven* and has callbacks so it's perfect for realtime applications. Use jQuery to request and post JSON from/to the server.

For example here we request data from the server as a JSON packet every second:

```

// callback when the JSON data has arrived
function getterCallback(result) {
    var temperatureArray = result.temperatures;
    // plot the array here
}

// timer callback (same idea as in Qt to define a refresh rate)
function getTemperature() {
    // get the JSON data
    $.getJSON("/data/:80",getterCallback);
}

// document ready callback
function documentReady() {
    // request new data from the server every second
    window.intervalId = setInterval(getTemperature , 1000);
}

// called when the web page has been loaded
$(document).ready( documentReady );

```

Mobile phone programming in JAVA, Kotlin or Swift is also purely callback driven as the JS code above and differs only in its syntax.

6.6 Conclusion

Events in web based communication are always triggered by the web browser or the mobile app in exactly the same way as Qt does it, for example by a button press. The same applies for animations where a client-side timer requests data from the server. Thus, these client side events either cause transmission of data from the web browser to the web server or request data from the web server. Nowadays the protocol is always http or https and a RESTful interface with JSON being the most popular data format.

Chapter 7

Setters

In Fig. 1.2 we have seen that data flows from the sensors to the C++ classes via *callbacks* then returns from the inner C++ classes to motor or display outputs is via *setters*. Setters are also used for setting configuration parameters.

A setter is a simple method in a class, for example to set the speed of a motor:

```
class Motor {  
    /**  
    * Set the Left Wheel Speed  
    * @param speed between -1 and +1  
    */  
    void setLeftWheelSpeed(float speed);  
};
```

Again as with callbacks it's important to *abstract* away from the hardware, for example normalising the speed of the motor between -1 and $+1$ and *hiding* away the complexity of the PWM or GPIO ports in the class.

If a setter has more than one argument, in particular for configuration, it's highly recommended to use a *struct* to set the values. For example setting the parameters of the ADS1115:

```
/**  
 * ADS1115 initial settings when starting the device.  
 */  
struct ADS1115settings {
```

```

/**
 * I2C bus used (99% always set to one)
 */
int i2c_bus = 1;

/**
 * I2C address of the ads1115
 */
uint8_t address = DEFAULT_ADS1115_ADDRESS;
};

/**
 * Starts the data acquisition in the background and the
 * callback is called with new samples.
 * \param settings A struct with the settings.
 */
void start(ADS1115settings settings = ADS1115settings() );

```

If a setter sets large buffers then it's highly recommended to allocate the memory in the constructor of the class and then call the setter by reference while running. Use array types which convey their length, for example `std::array` or a standard const array which implicitly carries their length.

Constant sampling rate output (audio, ...) There are many applications where the output device has a fixed sampling rate, for example digital to analogue converters. In this case the C++ driver class will again have a blocking write-loop periodically reading a buffer populated by the setter, which is ideally always ahead of time. You need to decide what happens if no fresh data has arrived, for example interpolating the output or putting it on hold. Of course you can also implement a callback by the audio write-loop to *request* samples but ultimately the conflict between audio arriving and being dispatched needs to be resolved.

7.1 Conclusion

Setters are simply methods which transmit an event back to the physical device. Setters should, as callbacks, always hide the low level complexity of the hardware device and receive normalised or physical units.

Appendix A

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