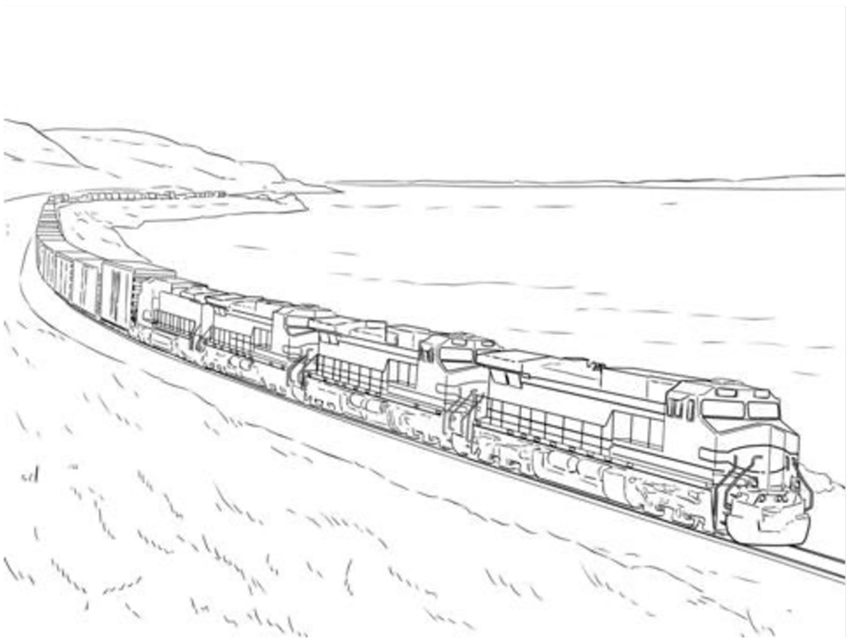

A Layout Control System for Model Railroads

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Contents

1 Introduction

Model railroading. A fascinating hobby with many different facets. While some hobbyist would just like to watch trains running, others dive deeper into parts of their hobby. Some build a realistic scenery and model a certain time era with realistic operations. Others build locos and rolling equipment from scratch. Yet others enjoy the basic benchwork building, electrical aspects of wiring and control. They all have in common that they truly enjoy their hobby.

This little book is about the hardware and software of a layout control system for managing a model railroad layout. Controlling a layout is as old as the hobby itself. I remember my first model railroad. A small circle with one turnout, a little steam engine and three cars. Everything was reachable by hand, a single transformer supplied the current to the locomotive. As more turnouts were added, the arm was not long enough any more, simple switches, electrical turnouts and some control wires came to the rescue. Over time one locomotive did not stay alone, others joined. Unfortunately, being analog engines, they could only be controlled by electric current to the track. The layout was thus divided into electrical sections. And so on and so on. Before you know it, quite some cabling and simple electrical gear was necessary.

Nearly four decades ago, locomotives, turnouts, signals and other devices on the layout became digital. With growing sophistication, miniaturization and the requirement to model operations closer and closer to the real railroad, layout control became a hobby in itself. Today, locomotives are running computers on wheels far more capable than computers that used to fill entire rooms. Not to mention the pricing. Turnout control and track occupancy detection all fed into a digital control system, allowing for very realistic operations.

The demands for a layout control system can be divided into three areas. The first area is of course **running** locomotives. This is what it should be all about, right? Many locomotives need to be controlled simultaneously. Also, locomotives need to be grouped into consists for large trains, such as for example a long freight train with four diesel engines and fifty boxcars. Next are the two areas **observe** and **act**. Track occupancy detection is a key requirement for running multiple locomotives and knowing where they are. But also, knowing which way a turnout is set, the current consumption of a track section are good examples for layout observation. Following observation is to act on the information gathered. Setting turnouts and signals or enabling a track section are good examples for acting on an observation.

Running, observing an acting requires some form of **configurations** and **operations** What used to be a single transformer, some cabling and switches has turned into computer controlled layout with many devices and one or more bus systems. Sophisticated layouts need a way to configure the locomotives, devices and manage operations of layouts. Enter the world of digital control and computers.

After several decades, there is today a rich set of product offerings and standards available. There are many vendors offering hardware and software components as well as entire systems. Unfortunately they are often not compatible with each other. Furthermore, engaged open software communities took on to build do it yourself systems more or less compatible with vendors in one or the other way. There is a lively community of hardware and software designers building hardware and software layout control systems more or less from scratch or combined using existing industry products.

1.1 Elements of a Layout Control System

Before diving into concept and implementation details, let's first outline what is needed and what the resulting key requirements are. Above all, our layout control system should be capable to simultaneously run locomotives and manage all devices, such as turnouts and signals, on the layout. The system should be easy to expand as new ideas and requirements surface that need to be integrated without major incompatibilities to what was already built.

Having said that, we would need at least a **base station**. This central component is the heart of most systems. A base station needs to be able to manage the running locomotives and to produce the DCC signals for the track where the running locomotive is. There are two main DCC signals to generate. One for the main track or track sections and one for the programming track. This is the track where a locomotive decoder can be configured. A base station could also be the place to keep a dictionary of all known locomotives and their characteristics. In addition to interfaces to issues commands for the running locomotives, there also need to be a way to configure the rolling stock.

Complementing the base station is the **booster** or **block controller** component that produce the electrical current for a track section. The booster should also monitor the current consumption to detect electrical shortages. Boosters comes in several ranges from providing the current for the smaller model scales as well as the larger model scales which can draw quite a few amps. There could be many boosters, one for each track section. The base station provides the signals for all of them.

The **cab handheld** is the controlling device for a locomotive. Once a session is established, the control knobs and buttons are used to run the locomotive. Depending on the engine model, one could imagine a range of handhelds from rather simple handhelds just offering a speed dial and a few buttons up to a sophisticated handheld that mimics for example a diesel engine cab throttle stand.

With these three elements in place and a communication method between them, we are in business to run engines. Let's look at the communication method. Between the components, called nodes, there needs to be a **communication bus** that transmits the commands between them. While the bus technology itself is not necessarily fixed, the messaging model implemented on top is. The bus itself has no master, any node can communicate with any other node by broadcasting a message, observed by all other nodes. Events that are broadcasted between the nodes play a central role. Any node can produce events, any node can consume events. Base station, boosters and handhelds are just nodes on this bus.

But layouts still need more. There are **signals**, **turnouts** and **track detectors** as well as **LEDs**, **switches**, **buttons** and a whole lot more things to imagine. They all need to be connected to the common messaging bus. The layout control system needs to provide not only the hardware interfaces and core firmware for the various device types to connect, it needs to also provide a great flexibility to configure the interaction between them. Pushing for example a button on a control field should result in a turnout being set, or even a set of turnouts to guide a train through a freight-yard and so on.

Especially on larger layouts, **configuration** becomes quite an undertaking. The **configuration model** should therefore be easy and intuitive to understand. The elements to configure should all follow the same operation principles and be extensible for specific functions. A computer is required for configuration. Once configured however, the computer is not required for operations. The capacity, i.e. the number of locomotives, signals, turnouts and other devices managed should be in the thousands.

Configuration as well as operations should be possible through sending the defined messages as well as a simple ASCII commands send to the base station which in turn generates the messages to broadcast via the common bus. A computer with a graphical UI would connect via the USB serial interface using the text commands.

1.2 Standards, Components and Compatibility

The DCC family of standards is the overall guiding standard. The layout system assumes the usage of DCC locomotive decoder equipped running gear and DCC stationary decoder accessories. Beyond this set of standards, it is not a requirement to be compatible with other model railroad electronic products and communication protocols. This does however not preclude gateways to interact in one form or another with such systems. Am example is to connect to a LocoNet system via a gateway node. Right now, this is not in scope for our first layout system.

All of the project should be well documented. One part of documentation is this book, the other part is the thoroughly commented LCS core library and all software components built on top. Each lesson learned, each decision taken, each tradeoff made is noted, and should help to understand the design approach taken. Imagine a fast forward of a couple of years. Without proper documentation it will be hard to remember how the whole system works and how it can be maintained and enhanced.

With respect to the components used, it uses as much as possible off the shelf electronic parts, such as readily available microcontrollers and their software stack as well as electronic parts in SMD and non-SMD form, for building parts of the system. The concepts should not restrict the development to build it all from scratch. It should however also be possible to use more integrated elements, such as a controller board and perhaps some matching shields, to also build a hardware module.

1.3 This Book

This book will describe my version of a layout control system with hardware and software designed from the ground up. The big question is why build one yourself. Why yet another one? There is after all no shortage on such systems readily available. And there are great communities out there already underway. The key reason for doing it yourself is that it is simply fun and you learn a lot about standards, electronics and programming by building a system that you truly understanding from the ground up. To say it with the words of Richard Feynman

"What I cannot create, I do not understand. – Richard Feynman"

Although it takes certainly longer to build such a system from the ground up, you still get to play with the railroad eventually. And even after years, you will have a lay out control system properly documented and easy to support and enhance further. Not convinced? Well, at least this book should be interesting and give some ideas and references how to go after building such a system.

1.4 Parts and Chapters

The book is organized into several parts and chapters. The first chapters describe the underlying concepts of the layout control system. Hardware modules, nodes, ports and events and their interaction are outlined. Next, the set of message that are transmitted between the components and the message protocol flow illustrate how the whole system interacts. With the concepts in place, the software library available to the node firmware programmer is explained along with example code snippets. After this section, we all have a good idea how the system configuration and operation works. The section is rounded up with a set of concrete programming examples.

Perhaps the most important part of a layout control system is the management of locomotives and track power. After all, we want to run engines and play. Our system is using the DCC standard for running locomotives and consequently DCC signals need to be generated for configuring and operating an engine. A base station module will manage the locomotive sessions, generating the respective DCC packets to transmit to the track. Layouts may consist of a number of track sections for which a hardware module is needed to manage the track power and monitor the power consumption. Finally, decoders can communicate back and track power modules need to be able to detect this communication. Two chapters will describe these two parts in great detail.

The next big part of the book starts with the hardware design of modules. First the overall outline of a hardware module and our approach to module design is discussed. Building a hardware module will rest on common building blocks such as a CAN bus interface, a microcontroller core, H-Bridges for DCC track signal generation and so on. Using a modular approach the section will describe the building blocks developed so far. It is the idea to combine them for the purpose of the hardware module.

With the concepts, the messages and protocol, the software library and the hardware building blocks in place, we are ready to actually build the necessary hardware modules. The most important module is the base station. Next are boosters, block controllers, handhelds, sensor and actor modules, and so on. Finally, there are also utility components such as monitoring the DCC packets on the track, that are described in the later chapters. Each major module is devoted a chapter that describes the hardware building blocks used, additional hardware perhaps needed, and the firmware developed on top of the core library specifically for the module. Finally, there are several appendices with reference information and further links and other information.

1.5 A final note

A final note. "Truly from the ground up" does not mean to really build it all yourself. As said, there are standards to follow and not every piece of hardware needs to be built from individual parts. There are many DCC decoders available for locomotives, let's not overdo it and just use them. There are also quite powerful controller boards along with great software libraries for the micro controllers, such as the CAN bus library for the AtMega Controller family, already available. There is no need to dive into all these details.

The design allows for building your own hardware just using of the shelf electronic components or start a little more integrated by using a controller board and other breakout boards. The book will however describe modules from the ground up and not use controller boards or shields. This way the principles are easier to see. The appendix section provides further information and links on how to build a system with some of the shelf parts instead of building it all yourself. With the concepts and software explained, it should not be a big issue to build your own mix of hardware and software.

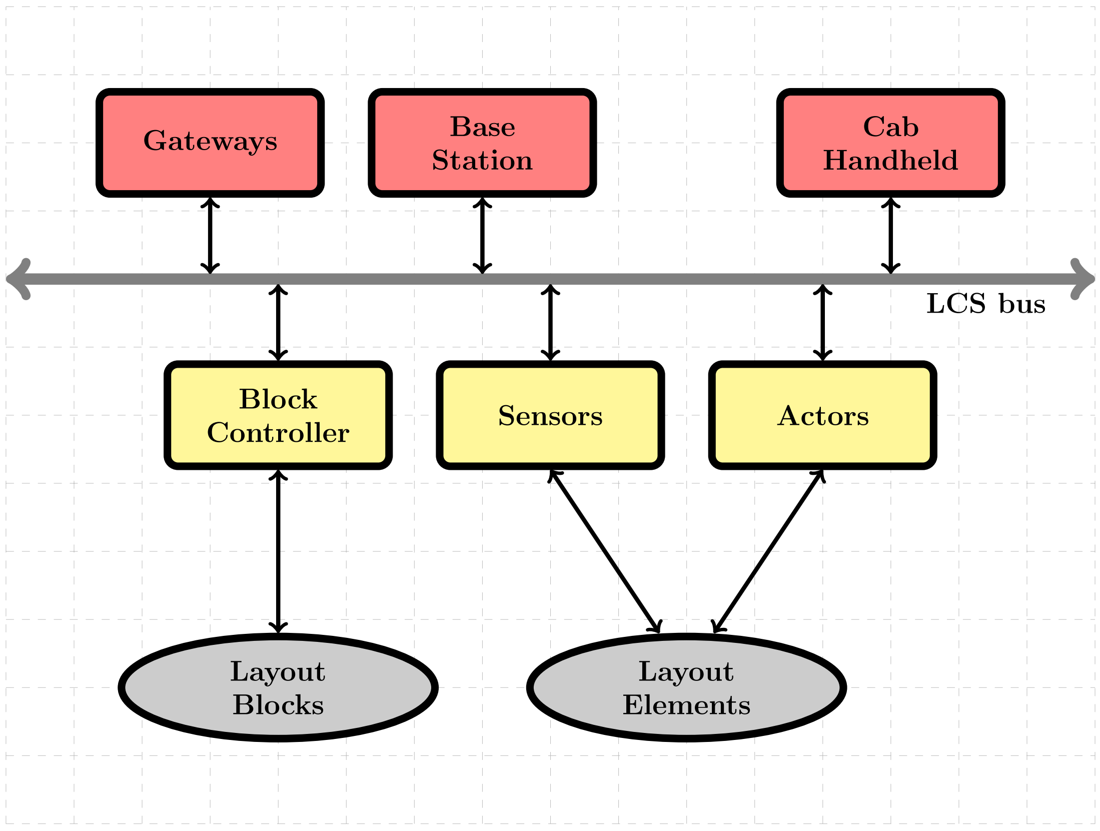
I have added most of the source files in the appendix for direct reference. They can also be found also on GitHub. (Note: still to do...) Every building block schematic shown was used and tested in one component or another. However, sometimes the book may not exactly match the material found on the web or be slightly different until the next revision is completed. Still, looking at portions of the source in the text explain quite well what it will do. As said, it is the documentation that hopefully in a couple of years from now still tells you what was done so you can adapt and build upon it. And troubleshoot.

The book hopefully also helps anybody new to the whole subject with good background and starting pointers to build such a system. I also have looked at other peoples great work, which helped a lot. What I however also found is that often there are rather few comments or explanations in the source and you have to partially reverse engineer what was actually build for understanding how things work. For those who simply want to use an end product, just fine. There is nothing wrong with this approach. For those who want to truly understand, it offers nevertheless little help. I hope to close some of these gaps with a well documented layout system and its inner workings.

In the end, as with any hobby, the journey is the goal. The reward in this undertaking is to learn about the digital control of model railroads from running a simple engine to a highly automated layout with one set of software and easy to build and use hardware components. Furthermore, it is to learn about how to build a track signaling system that manages analog and digital engines at the same time. So, enjoy.

2 General Concepts

At a higher level, the layout control system consists of components and a communication scheme. This chapter will define the key concepts of a layout system. At the heart of the layout control system is a common communication bus to which all modules connect. The others key elements are node, events, ports and attributes. Let's define these items first and then talk about how they interact. The following figure depicts the high level view of a layout control system.



2.1 Layout Control Bus

The layout control bus is the backbone of the entire system. The current implementation is using the industry standard CAN bus. All hardware modules connect to this bus and communicate via messages. All messages are broadcasted and received by all other hardware modules on the bus. The classic CAN bus standard limits the message size to 8 bytes and this is therefore the maximum message size chosen for the LCS bus. The CAN bus also has a hardware module limit of about 110 modules for bandwidth reasons. But even for a large layout this should be sufficient. And for really large layouts, another bus system or a system with CAN bus routers, could be envisioned. The software should therefore be designed to manage thousands of connected modules. While the CAN bus technology could be exchanged, the message format and size defined as well as the broadcasting paradigm are fixed in the overall design and will not change.

2.2 Hardware Module

Everything connected to the LCS bus is a **hardware module**, which is the physical entity connected to the bus. Typically it is a micro controller with the bus interface and hardware designed for the specific purpose. For example, a CAN bus interface, an AtMega Controller, and digital output drivers could form a hardware module to control railroad turnouts and signals. Base stations, handhelds and gateways are further examples of a hardware module. Hardware modules are expected to be physically located near their use and thus spread throughout the layout. Some hardware modules could be at locations that cannot be reached easily. So all interaction for configuration and operations needs to be possible through the messages on the bus. Nevertheless, putting local controls on a hardware module should not be prohibited.

A hardware module consists of a controller part and a node specific part. The controller part is the **main controller**, which consists of the controller chip, a non-volatile memory to retain any data across power down, a CAN bus interface and interfaces to the node specific hardware. The node specific hardware is called the **node extension**. Conceptually, both parts can be one monolithic implementation on one PCB board, but also two separate units connected by the extension connector. The are defined connectors between the boards. The hardware chapter will go into more detail on the board layouts and hardware design options.

2.3 Nodes

A hardware module is the physical implementation. A **node** is the software entity running in the firmware of the hardware module. Nodes are the processing elements for the layout. Conceptually, a hardware module can host more than one node. The current implementation however supports only one node on a given hardware module. A node is uniquely identified through the **node identifier**. There are two ways to set a nodeId. The first is to have central component to assign these numbers on request. The second method sets the number manually. Although a producer consumer scheme would not need a nodeId, there are many operations that are easier to configure when explicitly talking to a particular node. Both nodes and event identifiers are just numbers with no further classification scheme. A configuration system is expected to provide a classification grouping of nodes and event number ranges if needed.

A node also has a **node type**, to identify what the node is capable of. Examples of nodes types are the base station, a booster, a switch module, a signal control module, and so on. While the node number is determined at startup time and can change, the node type is set via the module firmware. As the node type describes what the hardware module can do the type cannot change unless the module changes. Once the node has an assigned node number, configuration tools can configure the node via configuration messages to set the respective node variables.

A node needs to be configured and remember its configuration. For this purpose, each node contains a **node map** that keeps all the information about the node, such as the number of ports, the node unique Id and so on. There is also a small set of user definable attributes to set data in a node map specific to the node. The data is stored in non-volatile memory space and on power up the node map is used to configure the node. If the module is a new module, or a module previously used in another layout, or the firmware version requires a new data layout of the node map, there is a mechanism to assign a new node number and initialize the node map with default values.

2.4 Ports

A node has a set of receiving targets, called ports. Ports connect the hardware world to the software world, and are the connection endpoints for events and actions. For example, a turnout digital signal output could be represented to the software as a port on a node. The node registers its interest in the event that target the signal. An event sent to the node and port combination then triggers a callback to the node firmware to handle the incoming events. Although a node can broadcast an event anytime by just sending the corresponding message, the event to send is typically associated with an outbound port for configuration purposes. In addition to the event immediate processing, the event handling can be associated with a timer delay value. On event reception the timer value will delay the event callback invocation or broadcast.

A node has a **port map** that contains one entry for each defined port. **port map entries** describe the configuration attributes and state of the port such as the port type. There is also a small set of user definable attributes to set data in a port map entry specific to the port. These attributes can be used by the firmware programmer to store port specific data items such as a hardware pin or a limit value in the port map.

2.5 Attributes

Node attributes and **port attributes** are conceptually similar to the CV resources in a DCC decoder. Many decoders, including the DCC subsystem decoders, feature a set of variables that can be queried or set. The LCS layout system implements a slightly different scheme based on items. In contrast to a purely decoder variable scheme an item can also just represent just an action such as setting an output signal. Items are passed parameter data to further qualify the item. Items are just numbers assigned. The range of item numbers is divided into a reserved section for the layout system itself, and a user defined range that allows for a great flexibility to implement the functions on a particular node and port. The meaning of user defined items is entirely up to the firmware programmer. If it is desired to have a variables, a combination of items and attributes can provide the traditional scheme as well. In addition, there are node local variables, called attributes, available to the firmware programmer for storing data items.

2.6 Events

The LCS message bus, hardware module, node and ports describe layout and are statically configured. For nodes to interact, **events** and their configuration is necessary. An event is a message that a node will broadcast via the bus. Every other node on this bus will receive the event and if interested act on the event. The sender is the producer, the receiver is the consumer. Many producers can produce the same event, many consumers can act on the same event. The **event Id**, a 16 bit number, is unique across the layout and assigned by a configuration tool during the configuration process. Other than being unique, there is no special meaning, the number is arbitrary. There are in total 65536 events available.

In addition to the event Id, an event message contains the node Id of the sender. While most events will be an ON/OFF event, events can also have additional data. For example an overload event sent by a booster node, could send the actual current consumption value in the event message. A consumer node registers its interest in an event by being configured to react to this event on a specific port. The node maintains an **event map**, which contains one entry for each event id / port id combination. For the eventing system to work, the nodeID is not required. Any port on any node can react to an event, any node can broadcast an event.

To connect producers to consumers, both parties need to be told what to do with a defined event. A producer node outbound port needs to be told what event to send for a given sensor observation. For example, a simple front panel push button needs to be told what event to send when pushed. Likewise, a consumer node inbound port needs to be told what events it is interested in and what the port should do when this event is received. Both meet through the event number used. While an inbound port can be configured to listen to many event Ids, an outbound port will exactly broadcast one eventId.

Any port on any node can react to an event, any node can broadcast an event. Still, addressing a node and port combination explicitly is required for two reasons. The first is of course the configuration of the node and port attributes. Configuration data needs to go directly to the specified node and port. The second reason is for directly accessing a resource on the layout. For example, directly setting a turnout connected to one node. While this could also be implemented with associated an event to send when operating a turnout, it has shown beneficial and easier to configure also directly access such a resource through a dedicated node/port address.

2.7 DCC Subsystem

The node, ports and events are the foundation for building a layout system based on the producer / consumer scheme. The scheme will be used heavily for implementing turnout control, signals, signal blocks and so on. In addition, there is the management of the mobile equipment, i.e. locomotives. The DCC subsystem is the other big part of our layout control system. In a sense it is another bus represented by the track sections.

LCS messages for DCC commands are broadcasted from controlling devices. For example, a handheld broadcasts a speed setting DCC command. In a layout there is one base station node which is responsible to produce the DCC signals for the track. The DCC signals are part of the physical LCS bus. While a base station design could directly supply the signal current to the track, larger layouts will typically have one or more boosters. They take the DCC signal from the LCS bus lines and generate the DCC signal current for their track section. All LCS messages for DCC operations are broadcasting messages, all nodes can send them, all nodes can receive them. Handhelds, base station and boosters are thus just nodes on the LCS bus. Only the base station will however generate the DCC signal.

The DCC standard defines mobile and stationary decoders. The DCC signal could also be used to control for example a set of turnouts via a stationary decoder. The LCS DCC message set contains messages for addressing a stationary decoder. Since the commands for stationary equipment are just DCC commands, they will be transmitted via the track as well and take away bandwidth on the track. A layout will therefore more likely use the LCS bus for implementing the management of stationary equipment. Besides, the producer / consumer model allows for a much greater flexibility when building larger and partially automated layouts.

2.8 Analog Subsystem

The layout control system is primarily a digital control system. There are however layout use cases where there are many analog locomotives that would represent a significant investment when converting to DCC or that cannot easily be equipped with a DCC decoder. In a DCC subsystem the decoder is in the locomotive and many locomotives can run therefore on the same track. In an analog system, the locomotive has no capabilities and therefore the track needs to be divided into sections that can be controlled individually. One locomotive per section is the condition. In a sense the decoder becomes part of the track section. The layout control system offers support for building such a track section subsystem. Often the sections are combined into blocks and build the foundation for a block signaling system. Note that the rest of the layout control system is of course digital. What is typically the booster to support a section of track, is the block controller for an analog layout. We will see in the later chapters that booster and block controller are very similar and design a block controller to accommodate both use cases.

2.9 Configuration Mode

Before operations the nodes, ports and events need to be configured. Once a node has an assigned valid nodeId, the node configuration is the process of configuring a node global information, the event map information and the finally the port information. The information is backed by non-volatile storage, such that there is a consistent state upon node power up. During operations, these value can of course change, but are always reset to the initial value upon startup.

The primary process of configuration is inventing events numbers and assigning them producers and consumers. The process follows the general "if this then that" principle. On the producer side the configuration process assigns a port to an event, i.e. the push of a button to an event to send. If this button is pushed then send that event. On the consumer side the configuration process is to assign the event to a port. If this event is received then execute that port action.

After the node is up and running with a valid node Id, there are event configuration messages than can be send to the node to set the event mapping table with this information. The event map table is the mapping between the event and the port associated. Events are thus configured by "teaching" the target node what port to inform about an occurring event.

2.10 Operation Mode

Besides the basic producer/consumer model with the event messages as communication mechanism, there are several LCS control and info messages used for managing the overall layout with signals turnouts and so on as well as the physical track and the running equipment. In a layout, the track typically consist of one or more sections, each managed by a booster or block controller node. Track sections are monitored for their power consumption to detect short circuits. Back communication channels such as RailCom are handled by the booster node and provide information about the running equipment. Stationary equipment such as turnouts and signals as well as detectors, such as track occupancy detectors or turnout setting detectors are monitored and controlled through LCS messages and the event system. Conceptually any node can send and receive such event, info or control messages. Some nodes, however have a special role.

For example, the key module for layout operations is the **base station**. The base station, a node itself, is primarily responsible for managing the active locomotives on the layout. When a control handheld wants to run a locomotive, a cab session for that locomotive is established by the base station. Within the session, the locomotive speed, direction and functions are controlled through the cab handheld sending the respective messages. The base station is responsible for generating the DCC packets that are sent by the booster or block controller power module to the actual track sections. Booster and block controller module are - you guessed it - node themselves.

Finally, there are LCS nodes that represent cab handhelds to control a locomotive or consists, layout panel connectors, gateways to other layout protocols, sensors and actors to implement for example turnout control, signaling, section occupancy detections and many more. All these components share the common LCS bus and use ports and events to implement the capabilities for operating a layout.

In a layout with many track sections the **block controller** is a special node that will manage a block on the layout. Like all other nodes, a block controller itself is a node that can react to events and is controller and monitored by LCS messages. There will be several chapters devoted to this topic later.

2.11 Summary

This chapter introduced the basic concepts of the layout control system described in this book. It follows very few overall guiding principles. Above all, there is the clear separation of what needs to be available for operating the mobile equipments, i.e. locomotives, and the stationary layout elements. Controlling mobile decoders are left to the DCC subsystem, all other communication takes place via the LCS bus, which is the bus to which all of the hardware modules connect. Hardware modules host the nodes. Currently, a hardware module hosts exactly one node. A node can contains one or many ports, which are the endpoints for the event system. There is a set of user allocated attributes available to node and ports. Node, port and attribute data are backed by non-volatile memory, so that a restart will use defined initial values. Nodes and their ports are also directly addressable, which is needed for configuration purposes and the directly addressable components model. Using the producer / consumer paradigm, sensors generate events and interested actors just act on them. The configuration process is simply to assign the same event to the producer node and consumer node / port id when they should work together.

The communication bus should rest on a reliable bus with a sufficient bandwidth. Although the CAN bus is used in the initial implementation, it is just one option and other technologies can be considered. In all cases however, the message format should be available for a variety of bus technologies. Our messages are therefore short, up to eight data bytes. This causes on the one hand some complexity for data items larger than a few bytes on the other hand no messages blocks the bus for a longer period. The bus technology is expected to reliably deliver a message but does not ensure its processing. This must be ensured through a request reply message scheme built on top.

3 Message Formats

Before diving into the actual design of the software and hardware components, let us first have a look at the message data formats as they flow on the layout control bus. It is the foundation of the layout control subsystem. This chapter will provide the overview on the available messages and give a short introduction to what they do. Later chapters build on it and explain how the messages are used for designing LCS node functions.

All nodes communicate via the layout control bus by broadcasting messages. Every node can send a message, and every node receives the message broadcasted. There is no central master.

a picture to show a node sending

Since all nodes receive all messages, a node needs to decide whether to react to a message or not. General management and emergency type messages are handled by all nodes. A reply to a specific request will only be handled by the requesting node. The layout control system defines a fairly large set of messages, which can be grouped into several categories:

- General management
- Node and Port management
- Event management
- DCC Track management
- DCC Locomotive Decoder management
- DCC Accessory Decoder management
- RailCom DCC Packet management
- Raw DCC Packet management

The current implementation is using the CAN bus, which ensures by definition that a message is correctly transmitted. However, it does not guarantee that the receiver actually processed the message. For critical messages, a request-reply scheme is implemented on top. Also, to address possible bus congestion, a priority scheme for messages is implemented to ensure that each message has a chance for being transmitted.

3.1 LCS Message Format

A message is a data packet of up to 8 bytes. The first byte represents the operation code. It encodes the length of the entire packet and opcode number. The first 3 bits represent the length of the message, the remaining 5 bits represent the opCode. For a given message length, there are 32 possible opcode numbers. The last opcode number in each group, 0x1F, is reserved for possible extensions of the opcode number range. The remaining bytes are the data bytes, and there can be zero to seven bytes.

The message format is independent of the underlying transport method. If the bus technology were replaced, the payload would still be the same. For example, an Ethernet gateway could send those messages via the UDP protocol. The messages often contain 16-bit values. They are stored in two bytes, the most significant byte first and labeled "xxx-H" in the message descriptions to come. The message format shown in the tables of this chapter just presents the opCode mnemonic. The actual value can be found in the core library include file.

The byte fields names in an LCS message are explained in greater detail when we discuss the runtime library. For this chapter, the term `npId-x` will refer to node/port identifier, the term `sId` to a locomotive session. The remaining message field names, such as `UID` or `spDir` are fairly self-explaining.

3.2 General Management

The general management message group contains commands for dealing with the layout system itself. The reset command `(RESET)` directs all hardware modules, a node, or a port on a node to perform a reset. The entire bus itself can be turned on and off `(BUS-ON, BUS-OFF)`, enabling or suppressing the message flow. Once the bus is off, all nodes wait for the bus to be turned on again. Finally, there are messages for pinging a node `(PING)`, perform data synchronization operations `(SYNC)` and request acknowledgement `(ACK/ERR)`.

Table 3.1: General Management

Opcode	Data1	Data2	Data3	Data4	Data5	Data6	Data7
RESET	npId-H	npId-L	flags				
BUS-ON							
BUS-OFF							
SYS-TIME	arg1	arg2	arg3	arg4			
LCS-INFO	arg1	arg2	arg3	arg4			
PING	npId-H	npId-L					
SYNC	npId-H	npId-L	arg				
ACK	npId-H	npId-L					
ERR	npId-H	npId-L	code	arg1	arg2		

Additional Notes

- Do we need a message for a central system time concept?
- Do we need a message for a message that describes the global LCS capabilities?
- Do we need an emergency stop message that every node can emit?

3.3 Node and Port Management

When a hardware module is powered on, the first task is to establish the node Id in order to broadcast and receive messages. The `(REQ-NID)` and `(REP-ID)` messages are the messages used to implement the protocol for establishing the nodeId. More on this in the chapter on message protocols. A virgin node has the hardware module-specific node type and a node Id of `NIL` also be set directly through the `(SET-NID)` command. This is typically done by a configuration tool.

Table 3.2: Node and Port Management

Opcode	Data1	Data2	Data3	Data4	Data5	Data6	Data7
REQ-NID	nId-H	nId-L	nUID-4	nUID-3	nUID-2	nUID-1	flags
REP-NID	nId-H	nId-L	nUID-4	nUID-3	nUID-2	nUID-1	flags
SET-NID	nId-H	nId-L	nUID-4	nUID-3	nUID-2	nUID-1	flags
NCOL	nId-H	nId-L	nUID-4	nUID-3	nUID-2	nUID-1	

All nodes monitor the message flow to detect a potential node collision. This could be for example the case when a node from one layout is installed in another layout. When a node detects a collision, it will broadcast the `(NCOL)` message and enter a halt state. Manual interaction is required. A node can be restarted with the `(RES-NODE)` command, given that it still reacts to messages on the bus. All ports on the node will also be initialized. In addition a specific port on a node can be initialized. The hardware module replies with an `(ACK)` message for a successful node Id and completes the node Id allocation process. As the messages hows, node and port ID are combined. LCS can accommodate up to 4095 nodes, each of which can host up to 15 ports. A Node ID 0 is the NIL node. Depending on the context, a port Id of zero refers all ports on the node or just the node itself.

The query node `(NODE-GET)` and node reply messages `(NODE-REP)` are available to obtain attribute data from the node or port. The `(NODE-SET)` allows to set attributes for a node or port for the targeted node. Items are numbers assigned to a data location or an activity. There are reserved items such as getting the number of ports, or setting an LED. In addition, the firmware programmer can also define items with node specific meaning. The firmware programmer defined items are accessible via the `(NODE-REQ)` and `(NODE-REP)` messages.

Table 3.3: Node and Port Management

Opcode	Data1	Data2	Data3	Data4	Data5	Data6	Data7
NODE-GET	npId-H	npId-L	item	arg1-H	arg1-L	arg2-H	arg2-L
NODE-PUT	npId-H	npId-L	item	val1-H	val1-L	val2-H	val2-L
NODE-REQ	npId-H	npId-L	item	arg1-H	arg1-L	arg2-H	arg2-L
NODE-REP	npId-H	npId-L	item	arg1-H	arg1-L	arg2-H	arg2-L

Nodes do not react to attribute and user defined request messages when in operations mode. To configure a node, the node needs to be put into configuration mode. The `(OPS)` and `(CFG)` commands are used to put a node into configuration mode or operation mode. Not all messages are supported in operations mode and vice versa. For example, to set a new nodeId, the node first needs to be put in configuration mode. During configuration mode, no operational messages are processed.

Table 3.4: Node and Port Management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
OPS	npId-H	npId-L					
CFG	npId-H	npId-L					

3.4 Event Management

The event management group contains the messages to configure the node event map and messages to broadcast an event and messages to read out event data. The (SET-NODE) with the item value to set and remove an event map entry from the event map is used to manage the event map. An inbound port can register for many events to listen to, and an outbound port will have exactly one event to broadcast. Ports and Events are numbered from 1 onward. When configuring, the portId `NIL` has a special meaning in that it refers to all portIds on the node.

Table 3.5: Event Management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
EVT-ON	npId-H	npId-L	evId-H	evId-L			
EVT-OFF	npId-H	npId-L	evId-H	evId-L			
EVT	npId-H	npId-L	evId-H	evId-L	arg-H	arg-L	

3.5 DCC Track Management

Model railroads run on tracks. Imagine that. While on a smaller layout, there is just the track, the track on a larger layout is typically divided into several sections, each controlled by a track node (centralized node or decentralized port). The system allows to report back the track sections status (in terms of occupied, free, and detecting the number of engines currently present). These messages allow the control of turnouts and monitoring of sections' status.

Table 3.6: DCC Track Management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
TON	npId-H	npId-L					
TOF	npId-H	npId-L					

3.6 DCC Locomotive Decoder Management

Locomotive management comprises the set of messages that the base station uses to control the running equipment. To control a locomotive, a session needs to be established `(REQ-LOC)`. This command is typically sent by a cab handheld and handled by the base station. The base station allocates a session and replies with the `(REP-LOC)` message that contains the initial settings for the locomotive speed and direction. (REL-LOC) closes a previously allocated session. The base station answers with the `(REP-LOC)` message. The data for an existing DCC session can requested with the `(QRY-LOC)` command. Data about a locomotive in a consist is obtained with the `(QRY-LCON)` command. In both cases the base station answers with the `(REP-LOC)` message.

Table 3.7: DCC Locomotive Decoder Management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
REQ-LOC	adr-H	adr-L	flags				
REP-LOC	sId	adr-H	adr-L	spDir	fn1	fn2	fn3
REL-LOC	sId						
QRY-LOC	sId						
QRY-LCON	conId	index					

Once the locomotive session is established, the `(SET-LSPD)`, `(SET-LMOD)`, `(SET-LFON)`, `(SET-LOF)` and `(SET-FGRP)` are the commands sent by a cab handheld and executed by the base station to control the locomotive speed, direction and functions. `(SET-LCON)` deals with the locomotive consist management and `(KEEP)` is sent periodically to indicate that the session is still alive. The locomotive session management is explained in more detail in a later chapter when we talk about the base station.

Table 3.8: DCC Locomotive Decoder Management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
SET-LSPD	sId	spDir					
SET-LMOD	sId	flags					
SET-LFON	sId	fNum					
SET-LFOF	sId	fNum					
SET-FGRP	sId	fGrp	data				
SET-LCON	sId	conId	flags				
KEEP	sId						

Locomotive decoders contain configuration variables too. They are called CV variables. The base station node supports the decoder CV programming on a dedicated track with the `(REQ-CVS)`, `(REP-CVS)` and `(SET-CVS)` messages. The `(SET-CVM)` message supports setting a CV while the engine is on the main track. `(DCC-ERR)` is returned when an invalid operation is detected.

Table 3.9: DCC Locomotive Decoder Management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
SET-LSPD	sId	cv-H	cv-L	mode	val		
REQ-CVS	cv-H	cv-L	mode	val			
REP-CVS	cv-H	cv-L	val				
SET-CVS	cv-H	cv-L	mode	val			

The SET-CVM command allows to write to a decoder CV while the decoder is on the main track. Without the RailCom channel, CVs can be set but there is not way to validate that the operation was successful.

3.7 DCC Accessory Decoder Management

Besides locomotives, the DCC standards defines stationary decoders, called accessories. An example is a decoder for setting a turnout or signal. There is a basic and an extended format. The `(SET-BACC)` and `(SET-EACC)` command will send the DCC packets for stationary decoders. Similar to the mobile decoders, there are POM / XPOM messages to access the stationary decoder via RailCom capabilities.

Table 3.10: DCC Accessory Decoder Management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
SET-BACC	adr-H	adr-L	flags				
SET-EACC	adr-H	adr-L	val				

These commands are there for completeness of the DCC control interfaces. There could be devices that are connected via the DCC track that we need to support. However, in a layout control system the setting of turnouts, signals and other accessory devices are more likely handled via the layout control bus messages and not via DCC packets to the track. This way, there is more bandwidth for locomotive decoder DCC packets.

3.8 RailCom DCC Packet management

With the introduction of the RailCom communication channel, the decoder can also send data back to a base station. The DCC POM and XPOM packets can now not only write data but also read out decoder data via the RailCom back channel. The following messages allow to send the POM / XPOM DCC packets and get their RailCom based replies.

Table 3.11: RailCom DCC Packet management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
SET-MPOM	sId	ctrl	arg1	arg2	arg3	arg4	
REQ-MPOM	sId	ctrl	arg1	arg2	arg3	arg4	
REP-MPOM	sId	ctrl	arg1	arg2	arg3	arg4	
SET-APOM	adr-H	adr-L	ctrl	arg1	arg2	arg3	arg4
REQ-APOM	adr-H	adr-L	ctrl	arg1	arg2	arg3	arg4
REP-APOM	adr-H	adr-L	ctrl	arg1	arg2	arg3	arg4

The XPOM messages are DCC messages that are larger than what a CAN bus packet can hold. With the introduction of DCC-A such a packet can hold up to 15 bytes. The LCS messages therefore are sent in chunks with a frame sequence number and it is the responsibility of the receiving node to combine the chunks to the larger DCC packet.

3.9 Raw DCC Packet Management

The base station allows to send raw DCC packets to the track. The `(SEND-DCC3)`, `(SEND-DCC4)`, `(SEND-DCC5)` and `(SEND-DCC6)` are the messages to send these packets. Any node can broadcast such a message, the base station is the target for these messages and will just send them without further checking. So you better put the DCC standard document under your pillow.

Table 3.12: RRaw DCC Packet Management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
SEND-DCC3	arg1	arg2	arg3				
SEND-DCC4	arg1	arg2	arg3	arg4			
SEND-DCC5	arg1	arg2	arg3	arg4	arg5		
SEND-DCC6	arg1	arg2	arg3	arg4	arg5	arg6	

The above messages can send a packet with up to six bytes. With the evolving DCC standard, larger messages have been defined. The XPOM DCC messages are a good example. To send such a large DCC packet, it is decomposed into up to four LCS messages. The base station will assemble the DCC packet and then send it.

Table 3.13: RRaw DCC Packet Management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
SEND-DCCM	ctrl	arg1	arg2	arg3	arg4		

3.10 DCC errors and status

Some DCC commands return an acknowledgment or an error for the outcome of a DCC subsystem request. The `(DCC-ACK)` and `(DCC-ERR)` messages are defined for this purpose.

Table 3.14: RRaw DCC Packet Management

Opcode	**Data1**	**Data2**	**Data3**	**Data4**	**Data5**	**Data6**	**Data7**
DCC-ACK							
DCC-ERR	code	arg1	arg2				

3.11 Analog Engines

The messages defined for the DCC locomotive session management as outlined above are also used for the analog engines. An analog engine will just like its digital counterpart have an allocated locomotive session and the speed/dir command is supported. All other commands will of course not be applicable. The speed/dir command will be sent out on the bus and whoever is in control of the track section where the analog engine is supposed to be, will manage that locomotive. In the following chapters we will answer the question of how exactly multiple analog engines can run on a layout.

3.12 Summary

The layout system is a system of nodes that talk to each other. At the heart are consequently messages. The message format is built upon an 8-byte message format that is suitable for the industry standard CAN bus. Although there are many other standards and communication protocols, the CAN bus is a widely used bus. Since all data is encoded in the message, there is no reason to select another communication media. But right now, it is CAN.

4 Message Protocols

This chapter will present how the messages presented in the previous chapter are used to form the protocols for layout configuration and operations. We begin with node management and port management. Next, the event system is described. Finally, the DCC locomotive and track management related commands and messages round up this chapter. The protocols are described as a set of high level messages flow from requestor to receiver and back.

4.1 Node startup

Node startup includes all the software steps to initialize local data structures, hardware components and whatever else the hardware module requires. To the layout system, the node needs to be uniquely identified across the layout. A configuration software will use the nodeId to manage the node. The `(REQ-NID)` and `(REP-NID)` messages are used to establish the nodeId on node startup. On startup the current nodeId stored in the module non-volatile memory is broadcasted. The `(REQ-NID)` message also contains the node UID. This unique identifier is created when the node is first initialized and all non-volatile data structures are built. The UID will not change until the node is explicitly re-initialized again.

After sending the `(REQ-NID)` message the node awaits the reply `(REP-NID)`. The reply typically comes from a base station node or configuration software. In fact, any node can take on the role of assigning nodeIds. But a layout can only have one such node in charge of assigning nodeIds. The reply message contains the UID and the nodeId assigned. For a brand new module, this is will the node nodeId from now on.

Table 4.1: Node startup

node	**base Station**
REQ-NID (nodeId, nodeUID) `->`	
	`<-` REP-NID (nodeId, nodeUID) or timeout

The nodeUID plays an important role to detect nodeId conflicts. If there are two modules with the same nodeId, the nodeUID is still different. A requesting node will check the `(REP-NID)` answer, comparing the nodeUID in the message to its own nodeUID. If the UID matches, the nodeId in the message will be the nodeId to set. Note that it can be the one already used, or a new nodeId. If the UIDs do not match, we have two nodes assigned the same nodeId. Both nodes will enter the collision and await manual resolution.

The above nodeId setup scheme requires the presence of a central node, such a base station, to validate and assign node identifiers. In addition, the nodeId can also be assigned by the firmware programmer and passed to the library setup routine. Once assigned, the node is accessible and the node number can be changed anytime later with the `(SET-NID)` command. All nodes are always able to detect a nodeId conflict. If two or more nodes have the same nodeId, each node will send an `(NCOL)` message and go into halted state, repeating the collision message. Manual intervention is required to resolve the conflict through explicitly assigning a new nodeId.

4.2 Switching between Modes

After node startup, a node normally enters the operation state. During configuration, certain commands are available and conversely some operational commands are disabled. A node is put into the respective mode with the `(CFG)` and `(OPS)` message command.

Table 4.2: Switching between Configuration and Operations mode

base Station		**target node**
CFG/OPS	->	
	<-	ACK/ERR (nodeId) or timeout

4.3 Setting a new Node Id

A configuration tool can also set the node Id to a new value. This can only be done when the node is configuration mode. The following sequence of messages shows how the node is temporarily put into configuration mode for setting a new node Id.

Table 4.3: Switching between Configuration and Operations mode

Base Station		**Node**
CFG (nodeId)	->	node enters config mode
	<-	ACK/ERR (nodeId) or timeout
SET-NID (nodeId, nodeUID) ->		
	<-	ACK/ERR (nodeId) or timeout
OPS (nodeId)	->	node enters operations mode
	<-	ACK/ERR (nodeId) or timeout

It is important to note that the assignment of a node Id through a configuration tool will not result in a potential node Id conflict resolution or detection. This is the responsibility of the configuration tool when using this command. The node Id, once assigned on one way or another, is the handle to address the node. There is of course an interest to not change these numbers every time a new hardware module is added to the layout.

4.4 Node Ping

Any node can ping any other node. The target node responds with an (ACK) message. If the nodeId is NIL, all nodes are requested to send an acknowledge (ACK). This command can be used to enumerate which nodes are out there. However, the receiver has to be able to handle the flood of (ACK) messages coming in.

Table 4.4: Node ping

requesting node		**target node**
PING	->	
	<-	ACK (nodeId) or timeout

4.5 Node and Port Reset

A node or individual port can be restarted. This command can be used in configuration as well as operations mode. The node or will perform a restart and initialize its state from the non-volatile memory. A port ID of zero will reset the node and all the ports on the node.

Table 4.5: Node and Port Reset

requesting node		**target node**
RES-NODE (npId, flags)	->	node or port is restarted
	<-	ACK (nodeId) or timeout

4.6 Node and Port Access

A node can interact with any other node on the layout. The same is true for the ports on a node. Any port can be directly addressed. Node/port attributes and functions are addressed via items. The are reserved item numbers such as software version, nodeId, canId and configuration flags. Also, node or port attributes have an assigned item number range. Finally, there are reserved item numbers available for the firmware programmer.

The query node message specifies the target node and port attribute to retrieve from there. The reply node message will return the requested data.

Table 4.6: Node and Port Access

requesting node		**target node**
QRY-NODE (npId, item)	->	
	<-	REP-NODE (npId, item, arg1, arg2) or timeout if successful else (ERR)

A node can also modify a node/port attribute at another node. Obviously, not all attributes can be modified. For example, one cannot change the nodeId on the fly or change the software version of the node firmware. The `(SET-NODE)` command is used to modify the attributes that can be modified for nodes and ports. To indicate success, the target node replies by echoing the command sent.

Some item numbers refer to functions rather than attributes. In addition, all firmware programmer defined items are functions. The `(REQ-NODE)` message is used to send such a request, the `(REP-NODE)` is the reply message.

Table 4.7: Node and Port Access

requesting node		**target node**
SET-NODE (npId, item, val1, val2)	->	
	<-	ACK/ERR (npId) or timeout

Table 4.8: Node and Port Access

requesting node		**target node**
REQ-NODE (npId, item, arg1, arg2)	->	
	<-	REP-NODE (npId, item, arg1, arg2) if successful, else ACK/ERR (npId) or timeout

4.7 Layout Event management

Events play a key role in the layout control system. Nodes fire events and register their interest in events. Configuring events involves a couple of steps. The first step is to allocate a unique event Id. The number does not really matter other than it is unique for the entire layout. A good idea would be to have a scheme that partitions the event ID range, so events can be be tracked and better managed. Consumer configuration is accomplished by adding entries to the event map. The target node needs to be told which port is interested in which event. A port can be interested in many events, an event can be assigned to many ports. Each combination will result in one event map entry. The `(SET-NODE)` command is used with the respective item number and item data.

Table 4.9: Layout Event management

requesting node		**target node**
SET-NODE (npId, item, arg1, arg2)	->	
	<-	REP-NODE (npId, item, arg1, arg2) if successful, else ACK/ERR (npId) or timeout

An entry can be removed with the remove an event map entry item in the `(SET-NODE)` message. Specifying a NIL portId in the messages, indicates that all eventId / portId combinations need to be processed. Adding an event with a NIL portID will result in adding the eventID to all ports, and removing an event with a NIL portID will result in removing all eventId / portID combinations with that eventId.

Producers are configured by assigning an eventId to broadcast for this event. The logic when to send is entirely up to the firmware implementation of the producer.

Even a small layout can already feature dozens of events. Event management is therefore best handled by a configuration tool, which will allocate an event number and use the defined LCS messages for setting the event map and port map entry variables on a target node.

Table 4.10: Layout Event management

requesting node		**interested node**
EVT-ON (npId, item, eventId)	`->`	receives an "ON" event
EVT-OFF (npId, item, eventId)	`->`	receives an "OFF" event
EVT (npId, item, eventId, val)	`->`	receives an event with an argument

4.8 General LCS Bus Management

General bus management messages are message such as `(RESET)`, `(BUS-ON)`, `(BUS-OFF)` and messages for acknowledgement of a request. While any node use the acknowledgement messages `(ACK)` and `(NACK)`, resetting the system or turning the bus on and off are typically commands issued by the base station node. Here is an example for turning off the message communication. All nodes will enter a wait state for the bus to come up again.

Table 4.11: General LCS Bus Management

requesting node		**any node**
BUS-ON (npId, item, eventId)	`->`	nodes stop using the bus and wait for the (BUS-ON) command
BUS-OFF (npId, item, eventId)	`->`	nodes start using the bus again

4.9 DCC Track Management

DCC track management messages are commands sent by the base station such as turning the track power on or off. Any node can request such an operation by issuing the `(TON)` or `(TOF)` command.

Table 4.12: DCC Track Management

requesting node		**any node**
TON (npId)	`->`	nodes or an individual node/port for a track section execute the TON command
TOF (npId)	`->`	nodes or an individual node/port for a track section execute the TOF command

Another command is the emergency stop `(ESTP)`. It follows the same logic. Any node can issue an emergency stop of all running equipment or an individual locomotive session. The base station, detecting such a request, issues the actual DCC emergency stop command.

In addition, LCS nodes that actually manage the track will have a set of node/port attributes for current consumptions, limits, and so on. They are accessed via the node info and control messages.

Table 4.13: DCC Track Management

requesting node		**any node**
ESTP(npId)	->	all engines on a node / port for a track section will enter emergency stop mode

4.10 Locomotive Session Management

Locomotive session management is concerned with running locomotives on the layout. The standard supported is the DCC standard. Locomotive session commands are translated by the base station to DCC commands and send to the tracks. To run locomotives, the base station node and the handheld nodes, or any other nodes issuing these commands, work together. First a session for the locomotive needs to be established.

Table 4.14: Locomotive Session Management

sending node		**bae station node**
REQ-LOC (locoAdr, flags)	->	
	<-	REP-LOC (sessionId, locoAdr, spDir, fn1, fn2, fn3)

When receiving a REQ-LOC message, the base station will allocate a session for locomotive with the loco DCC address. There are flags to indicate whether this should be a new session to establish or whether to take over an existing session. This way, a handheld can be disconnected and connected again, or another handheld can take over the locomotive or even share the same locomotive. Using the `(REP-LOC)` message, the base station will supply the handheld with locomotive address, type, speed, direction and initial function settings. Now, the locomotive is ready to be controlled.

Table 4.15: Locomotive Session Management

sending node		**base station node**
SET-LSPD(sId, spDir)	->	sends DCC packet to adjust speed and direction
SET-LMOD(sId, flags)	->	sends DCC packet to set session options
SET-LFON(sId, fNum)	->	sends DCC packet to set function Id value ON
SET-LFOF(sId, fNum)	->	sends DCC packet to set function Id value OFF
SET-FGRP(sId, sId, fGroup, data)	->	receives DCC packet to set the function group data
KEEP(sId)	->	base station keeps the session alive

The base station will receive these commands and generate the respective DCC packets according to the DCC standard. As explained a bit more in the base station chapter, the base station will run through the session list and for each locomotive produce the DCC packets.

Periodically, it needs to receive a `(KEEP)` message for the session in order to keep it alive. The handheld is required to send such a message or any other control message every 4 seconds.

Locomotives can run in consists. A freight train with a couple of locomotive at the front is very typical for American railroading. The base station supports the linking of several locomotives together into a consist, which is then managed just like a single loco session. The (SET-LCON) message allows to configure such consist.

Table 4.16: Locomotive Session Management

sending node		base station node
SET-LCON(sId, conId, flags)	`->`	send DCC packet to manage the consist

To build a consist, a consist session will be allocated. This is the same process as opening a session for a single locomotive using a short locomotive address. Next, each locomotive, previously already represented through a session, is added to the consist session. The flags define whether the locomotive is the head, the tail or in the middle. We also need to specify whether the is forward or backward facing within the consist.

4.11 Locomotive Configuration Management

Locomotives need to be configured as well. Modern decoders feature a myriad of options to set. Each decoder has a set of configuration variables, CV, to store information such as loco address, engine characteristics, sound options and so on. The configuration is accomplished either by sending DCC packets on a dedicated programming track or on the main track using with optional RailCom support. The base station will generate the DCC configuration packets for the programming track using the `(SET-CVS)`, `(REQ-CVS)`, `(REP-CVS)` commands. Each command uses a session Id, the CV Id, the mode and value to get and set. Two methods, accessing a byte or a single bit are supported. The decoder answers trough a fluctuation in the power consumption to give a yes or no answer, according to the DCC standard. The base station has a detector for the answer.

Table 4.17: Locomotive Session Management

sending node		base station node
SET-CVS(cvId, mode, val)	`->`	validate session, send a DCC packet to set the CV value in a decoder on the prog track
REQ-CVS(cvId, mode, val)	`->`	validate session, send a DCC packet to request the CV value in the the decoder on the prog track
	`<-`	REP-CVS(cvId, val) if successful or (ERR)

Programming on the main track is accomplished with the `(SET-CVM)` message. As there are more than one locomotive on the main track, programming commands can be send, but the answer cannot be received via a change in power consumption. One alternative for programming on the main track `( POM, XPOM )` is to use the RailCom communication standard. The base station and booster or block controller are required to generate a signal cutout period in the

DCC bit stream, which can be used by the locomotive decoders to send a datagram answer back. There is a separate section explaining this in more detail.

Table 4.18: Locomotive Session Management

sending node		**base station node**
SET-CVM(cvId, mode, val)	`->`	validate session, send a DCC packet to set the CV value in a decoder on the main track
	`<-`	if not successful DCC-ERR

4.12 Configuration Management using RailCom

Instead of configuring engines and stationary decoders on the programming track, i.e. a separate track or just a cable to the decoder, configuring these devices on the main track would be a great asset to have. A key prerequisite for this to work is the support of receiving RailCom datagrams from the decoder.

??? **note** to be defined... we would need LCS messages to support this capability...
??? one message could be the channel one message of a RC detector...

4.13 DCC Accessory Decoder Management

The DCC stationary decoders are controlled with the `(SET-BACC)` and `(SET-EACC)` commands. A configuration/management tool and handhelds are typically the nodes that would issues these commands to the base station for generating the DCC packets. The following sequence shows how to send a command to the basic decoder.

Table 4.19: DCC Accessory Decoder Management

sending node		**base station node**
SET-BACC(accAdr, flags)	`->`	validate decoder address, send the DCC packet to the accessory decoder
	`<-`	if not successful DCC-ERR

Since the layout control system uses the LCS bus for accessing accessories, these messages are just intended for completeness and perhaps on a small layout they are used for controlling a few stationary decoders. It is also an option to use a two wire cabling to all decoders to mimic a DCC track and send the packets for the decoders. On a larger layout however, the layout control system bus and the node/event scheme would rather be used.

4.14 Sending DCC packets

The base station is the hardware module that receives the LCS messages for configuring and running locomotives. The primary task is to produce DCC signals to send out to the track. In addition to controlling locomotives, the base station can also just send out raw DCC packets.

Table 4.20: Sending DCC packets

sending node		base station node
SEND-DCC3(arg1, arg2, arg3)	->	puts a 3 byte DCC packets on the track, just as is
SEND-DCC4(arg1, arg2, arg3, arg4)	->	puts a 4 byte DCC packets on the track, just as is
SEND-DCC5(arg1, arg2, arg3, arg4, arg5)	->	puts a 5 byte DCC packets on the track, just as is
SEND-DCC6(arg1, arg2, arg3, arg4, arg5, arg6)	->	puts a 6 byte DCC packets on the track, just as is

Sending a large DCC packet will use the **SEND-DCCM** message. The ”ctrl” byte defines which part of the message is send. The base station will assemble the pieces and then issue the DCC packet.

Table 4.21: Sending DCC packets

sending node		base station node
SEND-DCCM(...)	->	puts a 3 byte DCC packets on the track, just as is

Again, as the DCC packets are sent out without further checking you better know the packet format by heart. Perhaps put the NMRA DCC specification under your pillow.

4.15 Summary

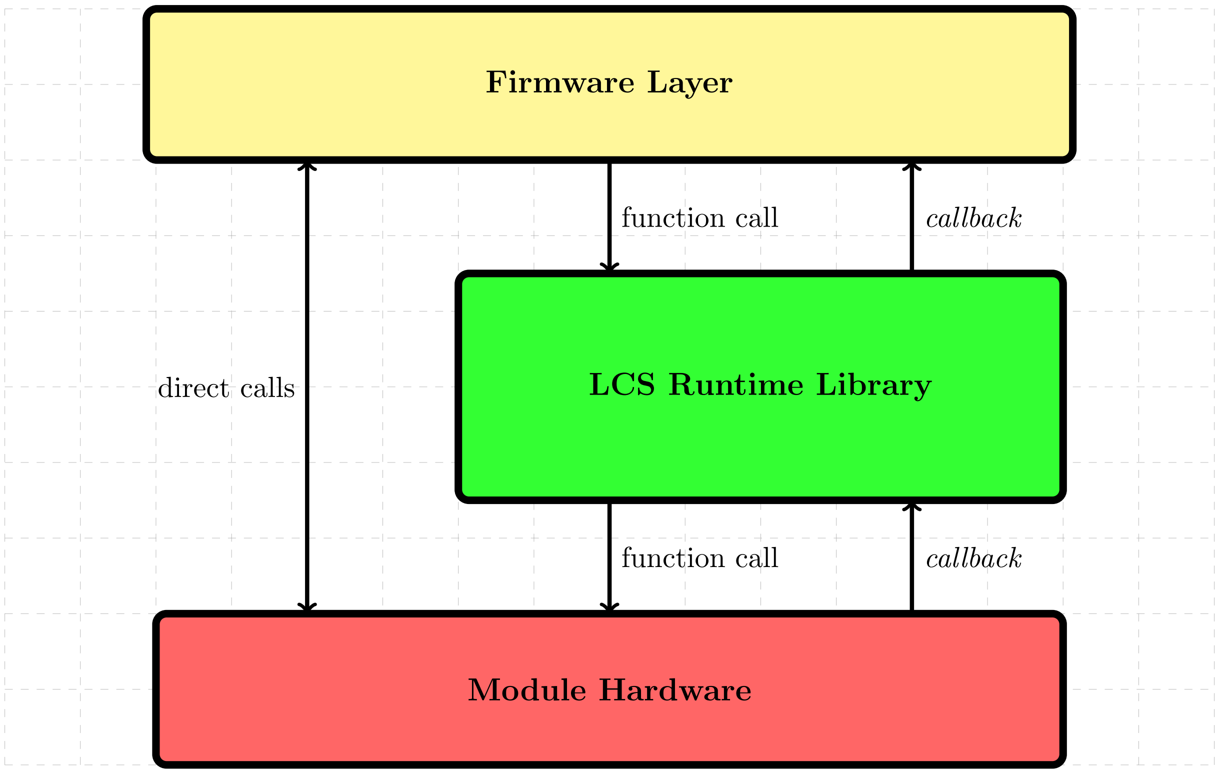
This chapter introduced the general message flow for the layout control bus functions. By now you should have a good idea how the system will work from a message flow between the nodes perspective. Most of the messages dealing with nodes, ports and events follow a request reply scheme using the nodeId as the target address. The DCC messages and protocols implicitly refer to nodes that implement base station and handheld functions. The base station is the only node that actually produces DCC packets to be sent to the track. However, any node implementing DCC functions can act on these messages. All message functions as well as functions to configure and manage nodes, ports and events are available for the firmware programmer through the **LCS Runtime Library**. The next chapter will now concentrate on the library concepts and functions.

5 The LCS Runtime Library RtLib

Intended for the node firmware programmer, the LCS runtime library is the main interface to the hardware module. The library has methods for node and port configuration, event processing and layout control bus management. Most of the LCS bus management, node, port and port data management is performed transparently to the node firmware programmer. The library also provides convenience methods to send messages to other nodes and allows for a rich set of callback functions to be registered to act on messages and events.

The key design objective for the runtime library is to relief the LCS nodes firmware programmer as much as possible from the details of running a firmware inside a hardware module. Rather than implementing the lower layers for storage and message processing at the firmware level, the runtime library will handle most of this processing transparently to the upper firmware layer. A small set of intuitive to use and easy to remember functions make up the core library. The library communicates back to the firmware layer via a set of defined callbacks. Throughout the next chapters, the library will be presented in considerable detail. Let's start with the high level view.

The following figure depicts the overall structure of a LCS hardware module and node. At the bottom is the hardware module, which contains the communication interfaces, the controller and the node specific functions. The core library offers a set of APIs and callbacks to the node firmware. The firmware programmer can perform functions such as sending a message or accessing a node attribute through the APIs provided. The library in turn communicates with the firmware solely via registered callbacks.



The firmware has of course also direct access to the hardware module capabilities. This is however outside the scope for the LCS core library. As we will see in the coming chapters, the library has a rich set of functions and does also perform many actions resulting form the protocol implementation transparently to the firmware programmer. It is one of the key ideas, that the firmware programmer can concentrate on the module design and not so much on the inner workings of the LCS layout system. Events, ports, nodes and attributes form a higher level foundation for writing LCS control system firmware. Not all of the functionality will of course be used by every node. A base station and a handheld cab control will for example make heavy use of the DCC commands. A turnout device node will use much more of the port and event system. Size and functions of the various library components can be configured for a node.

As a consequence, the library is not exactly a small veneer on top of the hardware and does take its program memory toll on controller storage. However, with the growing capabilities of modern controllers, this should not be a great limitation. The first working versions required an Arduino Atmega1284 alike version as the controller. The current working version is based on the Raspberry Pi Pico controller. More on the individual requirements and selection later.

The appendix contains the detailed description of all library interfaces. If a picture says more than a thousands words, an excerpt of the data declarations from the implementation says even more to the firmware programmer. At the risk of some minor differences on what is shown in the book and the actual firmware, you will find a lot of declarations directly taken from the "LcsRuntimeLib.h" include file.

6 The DCC Subsystem

The LCS runtime library builds the software foundation for implementing the layout control software. So far we have discussed the general working, node and port functions and callbacks. One part that was only touched upon briefly so far is the digital command control (DCC) subsystem. A significant part of the LCS messages deal with the control of running equipment decoder, stationary decoders and the track itself.

This chapter now dives a little deeper into the DCC subsystem. At the heart of this subsystem is the base station node that is in charge for of managing locomotives and tracks. It receives LCS messages from devices such as a cab throttle and translates these commands into a series of DCC packets. The packets are the basis for the DCC track power modules to actually produce the electrical signals on the track. The power module is either a part of the base station or a separate booster. Base station, boosters and throttles are just nodes making use of the DCC commands in the LCS message set. They too can implement reacting to events and send themselves events. First we will look at a base station and what it takes to manage a locomotive session and to generate the DCC packets for mobile and stationary decoders. Next, we will look into how a DCC packet actually gets out on the track.

6.1 Locomotive session management

Digital locomotives are equipped with a mobile decoder. The decoder will analyze the DCC packets on the track and if addressed perform the desired function. For each active locomotive the base station first establishes a locomotive session. Across the layout, a locomotive is uniquely identified by its **cabId**. In DCC terms this is the address of the locomotive. The DCC standard defines an address range that all decoders, mobile and stationary, share. Once a session is established for the cabId, the base station accepts LCS DCC commands, such as setting the speed, direction or a function, and produce the corresponding DCC packet. We will see later what happens to the packet.

A base station typically works with two DCC tracks. There is the **main track**, which consist of all the track sections of the layout. Commands such as setting a locomotive speed and direction, refer to this track. In addition, there is a **service track** which is used to configure an individual locomotive. This track is electrically separated from the main track. However, when it comes to packet transmission, the two tracks are very similar. For the base station functionality there are thus two key functional components. The first is the locomotive session management, the second is the programming of a locomotive mobile decoder. The programming track commands do not need a cabId, i.e. address, as there should only be one locomotive on this track. This has to do with the way a decoder replies the base station and will be discussed when we talk about decoder programming.

6.2 Stationary Decoders

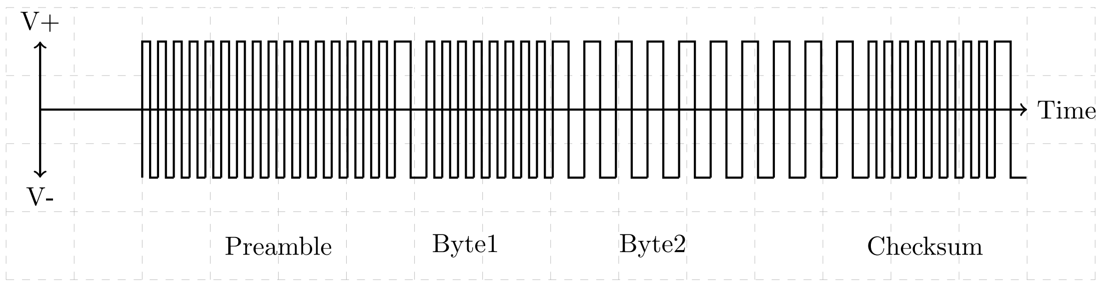
While mobile decoders can be found in a locomotive, a stationary decoder can be found somewhere on the layout. For example, a stationary decoder that is close to a set of turnouts. It is connected to the main track and just like its mobile cousin decodes the DCC packets. Stationary decoders, called accessories in the NMRA standard, are assigned to a part of the address range and react to their configured address. The base station accepts LCS commands for such a decoder and generates the DCC packets for it.

As said before, the trend is to use a layout control system with a dedicated bus for the layout components. The key idea is to offload the track where the engines run from the packets for the accessories. Another approach is to have a dedicated wire to all accessory decoders and send the DCC packets on this. In a sense another track without locomotives. Our layout control system will support generating the stationary decoders packets and send them via the main track. But the feature is only implemented for completeness. Maybe there is still one old decoders that is put to use this way. Our layout will be controlled by the LCS bus.

6.3 DCC packet generation

The key task of the locomotive session management is to generate the DCC packets for running and configuring mobile and stationary decoders. There are also packets, such as RESET or IDLE, that concern all decoders on the track. The DCC packets are described officially in the NMRA specifications. The *RailCommunity* specification documents (RCN-xxx) also have an excellent description of the packets layout and their interpretation. Each bit is either a zero or a one. A ”one” bit has a period of 116 microseconds, a zero bit a period of 232 microseconds. The exact timings are listed on the DCC standard, for now, this is a good enough description. The appendix contains links to their web pages for diving into all the details of the DCC packet format and protocol.

The base station part that produces DCC packets is not concerned with how these packets are actually transmitted to the locomotive. This is the task of the DCC track management component, which will be presented shortly. In general, a DCC packet is a stream of bits consisting of the preamble, a decoder address and the command bytes followed by a checksum byte. The preamble is to sync a decoder with the upcoming data stream. The address tells which decoder is address and the command bytes actually tell what needs to be done. Finally, the checksum makes sure that there was no error in transmitting the packet. The following figure depicts a simple packet.



The high level LCS DCC commands are translated by the base station into the corresponding DCC packets. There are two modes of transmission. With the first mode, any incoming command is translated and sent out immediately with an optional repeat count. Consider a locomotive speed stop command. This has of course top priority. The second mode of transmission is a one time fixed sequence of DCC packets for a high level LCS command, such as it is used for programming a decoder.

When no command is pending, the base station will loop through all active session entries and send packets for refreshing the previously sent commands. For example, after sending a speed/direction command, this command will be repeated periodically, until a new command is issued for this locomotive session. While looping through the session table, only a part of the necessary refresh packets are generated to make sure that all engines get a fair share of the track bandwidth in time. The complete refresh of speed/direction and function keys are spread over a couple of loop iterations. The DCC standard makes recommendations what data to send out how often or periodically. Time to discuss how the DCC packets actually get to the track.

6.4 Sending a DCC packet

The DCC track management software component does not store any DCC packets other than the active packet that is currently being transmitted and the pending next packet. If it is busy with sending a packet and there is already a pending packet queued, the packet loading routine in the locomotive session management component is waiting until the pending packet becomes the current packet and then the next packet is queued. There is one more scenario to address. Suppose there is no packet currently sent from the locomotive management and thus there is no packet to send to the track. In this case, we cannot just stop sending packets, as the locomotives draw their track power from the track signal. DCC track management signal generation then just "invents" a packet to send out. This is is the DCC IDLE packet for the main track and the DCC RESET packet for the programming track.

6.5 DCC Track Signal Generation

The primary task of a DCC track signal generator is to receive the DCC packets generated by the base station producing the hardware signals for the packet bits on the track. The other task is to monitor the power consumption and the optional RailCom channel communication. DCC signals are square wave signals with a defined duty cycle period. A duty cycle of 58 microseconds represents a "DCC one", a duty cycle of 116 microseconds a "DCC zero" bit. This signal is sent to the track by reversing the polarity of the two tracks lanes with the respective timing. Typically, a H-Bridge such as found in motor drivers will perform this task. If the H-Bridge is enabled, sending a "DCC One" will mean to set the digital input signals for the H-Bridge to enable the "+" direction, and then reverse the digital signals for the "-" direction. The H-Bridge hardware essentially reverses the track polarity accordingly to digital series and ones. The DCC packet is broken down, bit by bit and the digital signal is produced. That's it, we have a nice signal on the track. How exactly the base station does the digital signal output generation is discussed in more detail in the base station chapter.

6.6 Power consumption monitoring

DCC track management is also responsible for continuously monitoring the track power consumption. Considering that boosters can emit several Amps a short circuit for a longer time will certainly damage track and running equipment. It is therefore paramount to monitor the actual current consumption very closely. Monitoring track power consumption can be done by measuring the voltage drop over a shunt resistor in serial with the H-Bridge. The controller analog input will periodically read the value and process the incoming data. From a software perspective there are a couple of ways when to measure the voltage and how to process it. One way is to measure at defined spots in the bitstream.

During the signal generation, the track power current consumption will be measured at defined spots in the bit stream. A zero bit in a packet is a good place. The hardware just need to make sure that the measurement completes during the 116us half cycle of the zero bit. But certainly, there are other ways of measuring. When exceeding the configured consumption limit, it is stored in a node variable, DCC track management will broadcast a power overload event and shut down the track. After a configured time a restart is attempted. If the restarting fails for several times, the track is powered down permanently and manual intervention is required.

In addition, care needs to be taken to report a power consumption value that reflects the consumption over a period of time. Most locomotive decoder use a PWM (pulse width modulation) approach to drive the motor in the engine. Depending on when the current consumption measurement takes place a high level value or a zero value is returned. This does of course not reflect the actual power consumption. Therefore, several values sampled need to be used to build the "root mean square" value to indicate the actual power consumption.

6.7 Decoder programming support

There it is. A new locomotive unpacked, sitting on the programming track. At a minimum it needs to be told what its locomotive address will be on our layout. This task is accomplished by writing values to the decoder CV variables. A short locomotive address for example is a writing of this address to CV 1.

DCC is a broadcasting protocol. Just like a radio station, you can send but not receive. In order to communicate back the decoder raises its consumption power for specific value and time period to indicate an OK. DCC track management needs to be able to detect this consumption power fluctuation on the programming track. The detection is very similar to the previously discussed power consumption monitoring except that is done in two steps. Before accessing a CV variable, the current decoder power consumption is measured to establish a base line. This base line is then compared with the actual power consumption after the CV access. A fluctuation for the value and time specified by the DCC standard is considered a positive answer.

Reading all CV variables from a sophisticated decoder can easily take several minutes this way. Furthermore this communication will not work on the main track, as there are many locomotives running, making it impossible to detect the raise in power consumption of a single locomotive. There had to be a better way and there is. And there is. It is RailCom.

6.8 RailCom support

RailCom was invented to address the problem of effective back communication on the programming track and also on the main track. DCC track management needs to implemented the basic mechanism for this kind of communication. As the DCC is a broadcasting protocol, no other transmission is possible while it is broadcasting. The key idea of RailCom is to briefly turn off the DCC communication and use this moment of quiescence to transmit back data from the decoder. The period of short circuiting the DCC track is called the cutout period. In addition to to generating the DCC zeroes and ones on the track, DCC track management is also implementing the cutout support.

The following figure depicts the overall signal timing for RailCom support. All the details can be found in the NMRA and RailCommunity standard document including a hardware reference implementation for a RailCom decoder and detector. After the last bit of a packet and during the first bits of the DCC packet preamble, the track signal is turned off, the track is short circuited. The decoder can now send out data to the track and a signal detector can receive that data. The signal is a simple serial signal with a baud rate of 250 Kbits. The following figure shows the overall DCC and RailCom signal timing.

picture to come

The NMRA and RailCommunity standards describe the data format used when sending the RailCom data. There are two channels defined which in total send a maximum 8 bytes during the cutout period. Channel one takes up two bytes, channel two takes up four bytes. To ensure data transmission integrity, the bytes itself are encoded as values with four bits one and four bits zero. This leaves 64 useful values that the byte contains. All else is an invalid data byte. Put together, there are up to 48 bits of data in a RailCom message.

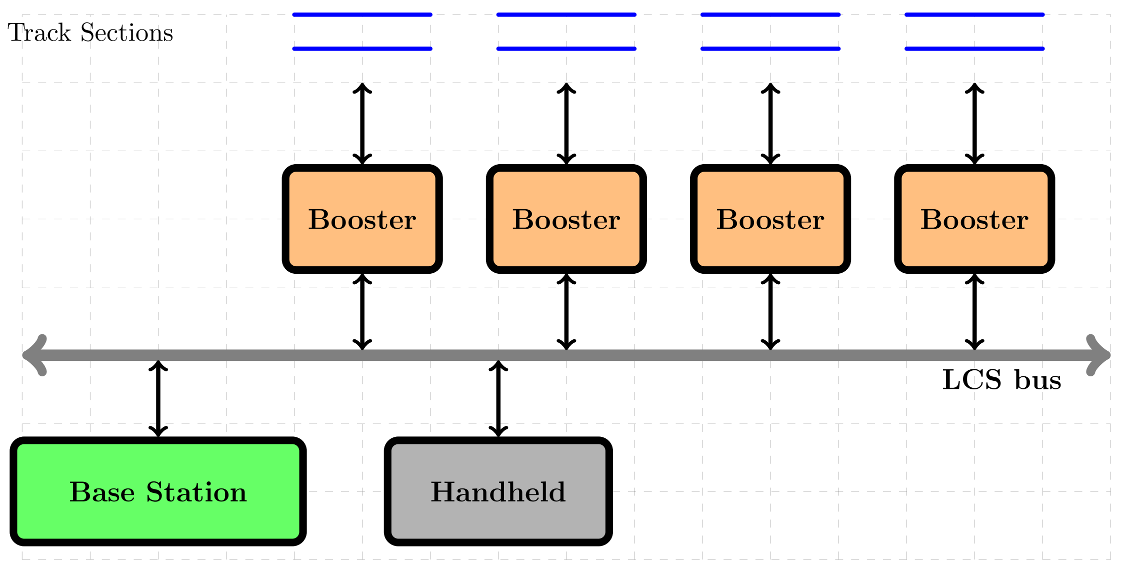
The individual messages available in channel one and two are called datagram. For channel one, a datagram is 12bits, i.e. the six bits encoded in the two raw data bytes, for channel two there are in total 36 bits. Each datagram tarts with a four bit identifier followed by the payload. A decoder is required to transmit its address every time it is addressed on channel one. Decoders will send data on channel two only of explicitly requested. This leaves channel one with a bit of chaos more than one decoder transmits. There are options to tell the decoder to stop sending its ID after an initial couple of times.

Channel two is only used when the decoder is explicitly addressed via an POM or XPOM DCC packet. Still, the base station needs to ensure that multiple requests form different encoders are transmitted one at a time and there is enough tie for the addressed decoder to answer. Als, the decoder needs to be addressed at least twice to complete a data request via RailCom. The first DCC packet tells what to get, the second DCC packet gives the controller a chance to put the RailCom reply in the next cutout packet. Finally, the DCC-A (`RCN218`) standard uses the RailCom infrastructure for automatic locomotive registration and fast access to the information in the decoder. For this purpose, channel one and two are combined to a 48bits payload data. More on these topics in the base station chapter.

6.9 DCC Track sections

A base station may have a powerful main track and a less powerful programming track. For smaller layouts this is a typical scenario. In fact, the DCC standard requires for the programming track to limit the maximum current to 100mA after initialization to avoid any decoder damage from misconfiguration when testing a new hardware. Larger layouts however are typically divided into several sections each of which is controlled by a DCC booster. This has the key benefit that a short circuit will only affect a track section. A DCC booster can also be equipped with a RailCom detector to implement for example locomotive detection on a per section basis.

To the DCC track management in a base station a booster managing a track section is largely transparent. All track management is concerned with is that the DCC signals are generated. A base station for a larger layout could just have two H-Bridges with a low current rating. One would produce the DCC signal for the main track, the other for the programming track. The programming track output is directly connected to the programming track. The main track output of the base station however is just a signal line that is then fed via the LCS bus data lines into the booster. All track sections will receive the same DCC signal. All boosters are required to be wired with the same track polarity.



All boosters will measure the power consumption continuously and in the case of exceeding the limits, send an event that the base station is interested in. Boosters are just LCS nodes like anything else. Port variables and events are the mechanism of communication. The actual implementation of a booster with variables and events are described in the hardware module chapter on boosters.

There is one more thing to take care of. If a layout consists of more than one track section there is the situation that the two boosters are not in close sync with respect to polarity and signal generation timing. Again, it is first of all very important that all boosters have a common polarity wiring. If not, short circuits caused by running equipment crossing from one section to the other are likely to happen. If RailCom is enabled, the cutout period acts as a short circuit of one section as well. If one booster section is in cutout mode and the adjacent booster not yet, crossing rolling equipment would effectively short circuit the active booster. To avoid this problem, boosters need not only be in close sync, the also should feature a kind of "security gap" period before starting the cutout period. In this period the booster is put into disconnected mode. This topic is also discussed a bit more in the booster hardware part.

6.10 A short Glimpse at Software Implementation

The DCC base station plays the key role in the DCC subsystem. In addition to manage the locomotive sessions and generating the necessary DCC packets, it is also responsible to manage the two tracks MAIN and PROG. Built on top of the LCS library, the base station will have two key software components, one for session management and one for track management. The session management part is rather straightforward, a table of active locomotive sessions that are processed periodically. The track management part is by nature very close to the hardware. Two interlinked state machines, one for track signal generation and one for track power management build the core of tack management. The actual implementation of the two key parts of the base station module is described in more detail in the base station chapter.

6.11 Summary

This chapter gave a high level overview on the DCC subsystem. The base station and booster firmware implement the DCC decoder management and track signal generation. Locomotive session management is concerned with managing the running equipment. The key concept is the session, which contains all data needed to control a locomotive on the track. DCC Packets for all active locomotives are generated and sent to the track management component and thereafter periodically refreshed. Programming a locomotive decoder sends a DCC packet sequence which the decoder addressed interprets. There are two tracks, the main track and the programming track. While they are a different in what they are used for and what hardware capacities they need, both will just as their key function putting out the packets generated by the locomotive session management software.

DCC track management is responsible for the track signal generation and track power management. It takes the DCC packets and sends them out bit by bit. First the preamble and optional cutout period then each data byte of the packet. The track consumption power is monitored for the main tack and also used for the programming track decoder acknowledge power consumption fluctuation. Exceeding the configured power consumption limits will result an a shutdown of the signal followed by a number of restarts. The DCC signals produced by the based station are ready to be used and can directly be fed to a track. However, in larger layouts, there will track sections with a DCC boosters for each section. Base station and boosters are, you guessed it, just nodes on the LCS Bus.

7 The Analog Subsystem

Analog? Yes, there is analog. Although the Layout Control System is a digital system with locomotives controlled via DCC, there are cases where implementing a layout based on controlling all rolling stock via DCC would mean to equip all your analog running engines with DCC decoders. Besides that it represents quite a considerable cost and converting some older locomotives is a real project in itself. Also, there are model railroad clubs with literally hundreds of locomotives. These layouts are analog and you will find miles of cables to a central control station. Converting all of the existing infrastructure in one swoop represents a considerable cost.

This chapter presents an overview for a subsystem managing analog locomotives. We will only focus on analog running equipment. Devices such as signals, turnouts and other stationary equipment is managed with the LCS node, port, event system, i.e. digital. This chapter will introduce extensions required to manage an analog and also a potentially hybrid layout.

7.1 Requirements

The first major difference to a DCC based system is that for a given track section there can only be one locomotive or consist. In contrast to a digital signal with a permanent flow of the square wave signal, an analog system will use a pulse width modulated (PWM) approach. A wider pulse width will make the engines run faster, a smaller pulse width makes it run slower. The signal contains no information about the actual engine and just delivers power corresponding to speed desired to the track section.

To still run several engines, the layout needs to be divided into several sections or blocks. Just as we divided a layout into sections with separate DCC boosters, analog layouts will control sections with a separate power module. It is not necessary to have a power module for each section, but the more sections and power modules the more analog engines could run simultaneously. Built on top, an analog layout often has a concept of blocks to run trains automated managed by a block signal control system. The blocks are often divided further into subsections and there are track occupancy detectors to know where the loco is within the block.

Just like their DCC cousin, analog track sections need special consideration when an engine is moving from one block to the next. For DCC track sections, each having a booster receiving the same DCC signal from the base station, there is a short window of power disconnect to address any small booster timing differences. For the analog world, the current section and the following one need to be also in sync for the engine to cross from one block to the next. The PWM signals, which deliver the power to the locomotive, need to be synchronized in order to avoid that one block still delivers power and the next block not quite yet. A locomotive would not run smoothly in that case.

An analog track block would also need to know the actual engine characteristics of the engine in a block. Each engine has different power consumption characteristics, so the speed is a function of engine type and actual train load. This track control mechanism is very closely associated with an overall block signaling control system. In fact, an analog system almost every time has a block signaling system implemented to manage several engines. Note that in an analog the smarts must be in the block controller and not in the engine. In a DCC system, the smarts is in the engine. In A DCC system the booster are there to address the overall power needed, dividing a layout into several power sections. In an analog system, the sections are there to address the need to run many engine simultaneously. There can only be one engine in a track sections or block.

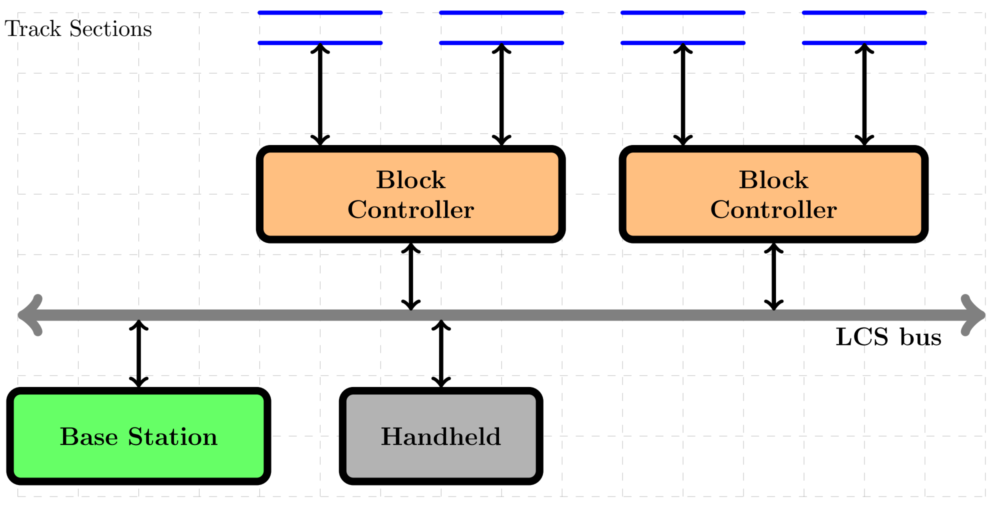
There is also the situation that a layout is in a transition from analog to digital. Wouldn't it be nice to manage both worlds in the same layout? A block could either host a DCC equipped locomotive or an analog locomotive, but never at the same time. Also, it needs to be ensured that the follow-on block where the engine is heading is of the right kind. This is brings up several more design questions, and we will talk about it in the following sections.

In any case, an analog system also needs a means of a cab handheld to control the engine. Following the LCS overall concept, the communication between the cab handheld and the layout nodes that ultimately control the engine, is digital. The concept of a locomotive session and a base station that manages all active sessions supports both DCC as well as analog engines. The base station managing locomotive sessions would need to be enhanced slightly to also support analog running equipment. Of course the cab handheld for an analog locomotive is much simpler. All that is needed is the direction and speed control.

7.2 Overall concept

Before diving into details, this section shows how support for an analog system could be implemented. There is the basis station managing all active locomotive sessions. The cab handheld will broadcast the speed / direction LCS message, which is received by the base station and translated to a DCC command packet sent out via the LCS bus. From an overall perspective, there is no difference in managing a locomotive session. There is still a handheld to set the speed and direction and there is a central place that is aware of all active sessions.

However, an analog engine has no concept being directly addressable. The typical solution is to divide the track into sections and control the sections where the locomotive currently is. The section is called a block and a block itself consist of one or more sub sections. The track subsections each have a sensor to detect that there is something drawing current from the track and the block controller has a way to know which locomotive is in which block. The following figure depicts an analog layout using the LCS components.



The LCS base station that manages all active locomotives, will not work differently for a digital or analog locomotive. It will create a session and also emit DCC data packets for controlling among other thongs speed and direction. The DCC signal is broadcasted via the LCS bus. This way it will also reach all block controllers that manage a block. The block controller will then decode the DCC packet and if it concerns a locomotive that according to the block controller data is currently in the block will put the respective PWM signal on the track. This is different to a normal DCC booster. A DCC booster just amplifies the incoming DCC signal and puts it onto the track. A block controller will decode the DCC signal and put a corresponding PWM signal on the track.

7.3 Locomotive session management

For each active locomotive the base station first establishes a locomotive session. Across the layout, a locomotive is uniquely identified by its **cabId**. Once a session is established for the cabId, the base station accepts LCS commands for setting the speed and direction. This is common to both the DCC digital and analog control of a locomotive as far as the base station is concerned. The only difference is that for an analog engine, only speed and direction can be set. All other capabilities such as sound control and functions for turning on and off a headlight are not available.

7.4 Analog Track Signal Generation

The analog track signal does not contain any information transmitted via the signal. The signal is just a pulse width modulated electrical current. The wider the pulse the faster the engines will go. The direction is determined through the polarity of the track. Just like emitting a DCC signal waveform, the H-Bridge of the power modules can easily also emit a pulse width signal with the right polarity. Short circuit detection and power consumption measurement work independent of the kind of signal emitted.

7.5 Analog Track Blocks and Track subsections

Layouts with analog engines will almost certainly have a number of blocks that can be powered individually. There is a one to one relationship of a power module with a block. A block is further divided into a number of track subsections with occupancy detectors, so the locations where power is drawn within the block can be determined. The chapter on block controller and block signaling will pick up this topic in more detail.

Just like the DCC subsystem, care needs to be taken when a locomotive crosses from one block fed from a power module to the next block fed by another power module. The actual current put on the tracks needs to be in sync, such that there is not awkward jump or worse current flow between the blocks connected via the locomotive wheels when crossing. It needs a way of synchronizing the PWM signals. Classic analog block control system transmitted a separate signal for all block controllers. In our world, the DCC signal emitted to all block controller nodes throughout the LCS layout via the LCS bus is our synchronization method.

7.6 A short Glimpse at Software Implementation

The block controller is the heart of managing a block in an analog layout. It will be responsible for managing the track block with a number of subsections. Using the LCS event system, blocks communicate and broadcast data about the locomotive entering and leaving their block. Using defined node and port attributes, they also communicate about block occupancy. Turnout control and position feedback as well as track signal control are also be the part of the duties of a block controller.

A part of the block controller firmware will decode LCS messages to determine if there is a command that concerns a locomotive that according to the block controller data is currently managed by that block. Note that there is no way to really know that this is the locomotive until there is some mechanism of identifying a locomotive when entering a block. For example, the sending block where the locomotive is coming from sends an event that this locomotive has left the block. Consequently, the receiving block knows the locomotive ID and broadcasts the event of arrival.

Another part of the block controller firmware needs to manage the power module. Depending on the locomotive characteristics the speed and direction are set. Short circuiting and power consumption are measured just like it is done in a DCC subsystem. I addition the PWM signal phase needs to be the same in all blocks. This is accomplished by a common synchronization signal.

Finally, the firmware will track that a train truly left the block. This information is a combination of the follow-on block indicating that the train entered and a computed time interval where the train should have completely left the previous block has passed. If this is not the case, perhaps the train derailed or a part of it decoupled.

7.7 Summary

Analog systems have their purpose also in a digital world. The approach taken by the Layout Control Systems is to put the smarts of managing the running equipment of such a layout into a set of block controllers with the base station and cab handhelds transparently supporting DCC equipped and analog engines. Both worlds use the power module for managing the track current delivery and consumption measurement. While for DCC the power module generates an amplified copy of the DCC signal, it will generate a PWM signal for an analog engine.

The block controller takes on part of the duties of a DCC locomotive decoder in a digital layout. The DCC signal broadcasted to all nodes in the layout is simply decoded and matched with the locomotive information of the respective block controller. All block controllers constantly broadcast via the LCS event mechanism their current state.

Not discussed yet, there needs to be a central configuration system that keeps all the data about all blocks and their relation to each other. There also needs to be a dictionary of all locomotives and their characteristics. On top configuration software and also panels to set track routines and so on. The requirements will be discussed in the block signaling chapter.

8 LCS Hardware Module Design

So far we covered the general concepts, messages, protocols as well as the LCS core library and a glimpse how all of this might be used. Let's take a break from all that concepts and mostly software talk. For the software to run, hardware modules need to be built. Welcome to the next big part of this book. Here, we will talk about the lCS hardware modules. A hardware module conceptually consist of three key parts.

- communication
- controller
- function block(s)

At the center of a hardware module is the **controller**. There is a great variety of controllers and development environments available. When selecting a controller for LCS, we will talk in a minute which one was picked, its is important that there is enough CPU power and equally important a powerful development environment. A console command line interface and interfaces to load the software is also very handy for configuring, monitoring and debugging. The **communication** part implements at a minimum the LCS message bus interface for the messages to transmit between the modules. Finally, the **function block**s implement the hardware module specific capabilities.

This chapter is the first in series of chapters on hardware modules. Instead of presenting complete schematics for each major hardware module, such as the base station, we will go a slightly different route. We will first present the basic components an LCS node might need. Definitively we will need a controller and a CAN bus interface. Some LCS nodes might make use of an extended non-volatile storage, others need plenty of digital outputs. Just like Lego Blocks, all these parts should be combined easily to form the desired LCS hardware module. We will tackle each component one at a time to understand how they work. The later chapters will just combine these basic blocks with minor adaptations and perhaps some very dedicated components for their functionality.

8.1 Selecting the controller

The module designs described in this book initially used the AtMega controller platform along with the Arduino IDE to write the software. There is the Arduino IDE and by now a whole set of different processors. Since it was released, the Atmega controller family and boards such as Arduino UNO, Arduino NANO, Arduino MEGA are in widespread use. The LCS core library program and non-volatile storage requirements do place however a higher demand on the controller capabilities.

Meanwhile, the Raspberry PI Pico (`PICO`) controller joined the club. And it has a lot to offer. The PICO is a dual core controller running at up to 133 Mhz. It features a whopping 16Mbytes of flash and 264 Kbytes of main memory. There are plenty of IO ports, and functional blocks for UARTS, SPI and I2C interfaces. What makes this controller especially interesting are the PIO state machines that allow for implementing your own I/O protocols. There is CAN bus software library built using these state machines. This way no extra CAN bus controller is needed. The PICO comes with its own software development kit and also an Arduino IDE integration is available.

As time goes by, there will be for sure other capable controller entering the market. However, when you want to complete a project versus chasing the latest controllers, you will need to pick. In our case, the PICO is the controller of choice. Its capabilities match our requirements and will be a good choice for the years to come. nevertheless, the LCS library software should be designed as independent of a particular controller as possible. More on this later.

8.2 The Controller Platform

The following table gives some guidance on the capabilities needed in our designs. This list also applies in general to other controllers.

Table 8.1: Controller Attributes

Attributes	**Notes**
Processor	For a typical module, the PICO offers plenty in terms of CPU power. Since we use a software implementation for the CAN bus, running the software in one core and the CAN bus state machine in the other will well match what the PICO offers.
Memory	Memory depends on the size requirements of the node, port and event maps and the node-specific firmware data demands. A simple module would perhaps get by with 2Kb, a base station could easily use 32Kb or even more.
Program Memory	The LCS library already uses round about 64Kb of code storage. A simple module would get by with 32Kb, a base station could easily use 128Kb and more.
External NVM	Additional NVM storage is allocated in a separate EEPROM or FRAM. The capacity is highly dependent on the module use case. External NVM components typically also require the SPI or I2C interface. Most external EEPROM chips have write cycles of more than a million. At a minimum, a chip size of 32Kb is recommended. The PICO does not offer an internal EEPROM, so an external NVM is always required.
Digital channels	The bulk of control lines is digital and used heavily. For some hardware modules, a subset of the digital pins should also be PWM capable.
Analog channels	Analog input is typically used for the power module for analog voltage measurements. Otherwise, it is perhaps optional. The PICO allows for only three inputs. If more are desired, an external multiplexer needs to be implemented.
I2C	The I2C interface comes in very handy to connect a large variety of chips. Communication to the external NVM and also to chips that implement functions such as a servo controller will require this bus.

Continued on next page

Attributes	Notes
Serial I/O	The serial I/O is used in some hardware modules for implementation of RailCom detectors. The PICO features two hardware UARTS and the option to implement more in software using the PIO state machines.
Console I/O	Serial I/O is used for console I/O. Rather than using dedicated I/O pins and a UART block in the controller, the PICO serial I/O will be implemented via the USB connector.
LEDs, Button and Dip Switches	A hardware module could make use of LEDs to indicate readiness and activity, as well as a set of switches to configure a hardware option. Not really required but certainly useful.
WLAN	WLAN is optional. But there is a PICO version with WLAN capability integrated.

8.3 Hardware Module Schematics

Hardware modules are described to large extent via schematics. The schematics shown in the following chapters are all drawn with the EasyEDA software. It is a great hardware development platform, and you can order PCBs for the final design in one easy step. Following a building block principle, the schematic diagrams will show functional components with many network endpoints where they connect to other building blocks. Each network endpoint is labelled with a name that is unique across all building blocks used in a hardware module schematic drawn. For example, "VCC-3V3" will always refer to the 3.3V power supply line. If two building blocks have an endpoint with the same name, the endpoints will be connected on all building block schematics in the final hardware module design.

A general word to the building blocks. They serve as examples of how the individual parts could be implemented and help to understand how each part works. Parts of the library software assume the presence of these blocks and how they basically work. Although the library has been written with as much as possible independence of the hardware, the final adaption of timers, serial lines, I/O pins and so on is required needs to be considered. Throughout the next chapters, you will find comments on what is perhaps generic and what would require some adaption if moving to another processor family.

8.4 Controller and Extension Board

Each node in the layout control system is a node and hence there is a controller for running the node firmware. Without a question, there will be many different nodes and as time goes by perhaps even a new controller families. However, each node would need at least some form of power supply, the CAN bus interface and depending on the storage demands and controller family, an external NVM. On top there is the node specific hardware. One approach is to design a board for each dedicated purpose. This board would include all the common portion for a LCS node and the hardware module specific portion. Another approach is to design a node controller board with extension boards that can be connected to it. In the remainder of this chapter, we will describe the main controller and extension concept. However, it is also perfectly all-right to design a hardware component with all the components integrated on one board. For a complex node such as the base station, this is a very reasonable solution. The building blocks shown in this chapter thus also form the basis for a more monolithic hardware module design. But first, let's look at the physical dimension of our boards.

picture

All boards will have a form factor of 10cm wide and 8, 12, and 16cm long. In particular, the 10x16cm board should be very familiar. It has the "Euro PCB" dimensions. The main controller board has on the left side the connectors for the LCS bus and the power input. On the right side, there are two connectors toward an extension board. As described before, there are two types of extension boards. The usage of the individual connector pins are described in the upcoming chapter. To ease the hardware schematic development and ensure that all boards fit together, the PCB boards along with their connectors are available as symbols and PCB footprints in the EasyEDA library.

8.5 LCS Bus connector

Every hardware module needs the LCS bus interface to connect to the bus. Some modules may also draw power from this bus. The modules use an RJ45 connector for connecting to the bus. The bus signals can be grouped in several categories. The CAN bus differential lines represent the CAN bus. The VS line is intended for hardware modules with very little power consumptions so that they can directly be powered by the bus. The DCC signal lines are an exact copy of the DCC signal that would go to a track sent out by the DCC signal generating base station. The signal is intended to be routed from the base station to booster nodes, but also to hardware modules that analyze the DCC signal for some action. Finally there is the STOP signal line. This is a wired OR line that allows a simple button along the layout with access to this line to issue a STOP signal. The base station or any nodes interested in the signal can monitor this line. There are the following signal lines.

Table 8.2: Bus Connector Pins

Pin	**Name**	**Purpose**
1	DCC-Sig-1	The DCC signal labelled "+"
2	DCC-Sig-2	The DCC signal labelled "-"
3	GND	Common ground
4	RSV	reserved for future extensions.
5	RSV	reserved for future extensions.
6	PWR	The bus supplied 12V power line. This line is intended for devices with very little power consumption to get their power from. Any other module should connect to its own power supply line.
7	CAN-L	Line L of the differential CAN bus signal.
8	CAN-H	Line H of the differential CAN bus signal.

8.6 LCSNodes Extension Board Connector

For interchangeability of extensions, there is a standardized **extension board connector** between controller and extensions. Extension boards come in two flavors. The first will have the extension connector on both sides of the board. Main controller boards and extension board will have a female connector on the right hand side. The first flavor extension board will have a matching connector on the left side. This way main controller and extension boards can be placed next to each other, just like a train. The second type of extension boards only have the connectors on the right hand side. They are intended for a backplane style layout where main controller and extension boards are plugged next to each other. The overall concept is very similar to the the shield concept found in the Arduino or Raspberry PI universe, except that we can stack boards, as well as placing them next to each other.

The I2C interface will be the main communication method between the boards. In fact all current extension boards shown in later chapters use the I2C communication channel. Nevertheless, a rather rich set of outputs from the controller should be available to the extension board for flexibility. There should be ports for digital input and output, analog input, PWM outputs, serial outputs and so on. The raspberry pi pico offers a great flexibility on assigning function blocks such as an SPI or I2C interface to pins. The extension connector outlined below offers a set of pins which are mapped to the PICO capabilities. The following table shows the connector pin assignments for the communication between a main controller board and extension boards. All boards will have a 40-pin connector organized as 2 rows of 20 pins.

Table 8.3: Extension Connector

Pin	**Name**	**Pin**	**Name**	**Purpose**
1	**DCC-1**	2	**DCC-2**	The DCC "+" and "-" signal as generated by the DCC Signal Generator. These pins are typically driven by the base station generating the layout DCC signal.
3	**GND**	4	**GND**	Common ground pins.
5	**ADC-0**	6	**ADC-1**	Analog input pins. The input is not protected. The analog voltage range is 0 to VCC.
7	**GND**	8	**GND**	Common ground pins.
9	**DIO-0**	10	**DIO-1**	Plain digital Pins, input or output. The pins are protected.
11	**DIO-2**	12	**DIO-3**	Plain digital Pins, input or output. The pins are protected.
13	**DIO-4**	14	**DIO-5**	Plain digital Pins, input or output. The pins are protected.
15	**DIO-6**	16	**DIO-7**	Plain digital Pins, input or output. The pins are protected.
17	**DIO-8**	18	**DIO-9**	Plain digital Pins, input or output. The pins are protected.
19	**DIO-10**	20	**DIO-11**	Plain digital Pins, input or output. The pins are protected.
21	**GND**	22	**GND**	Common ground pins.

Continued on next page

Pin	Name	Pin	Name	Purpose
23	**BI-0**	24	**BI-1**	Bus Address input lines. Up to four extension boards can be connected, the BI pins are used to determine the I2C address on the I2C extension bus.
25	**BO-0**	26	**BO-1**	Bus Address output lines. The BO lines are computed form the BI lines. If for example BI is 1:0 the BO lines will become 1:1. The starting output pins values are 1:1.
27	**SCL**	28	**SDA**	I2C extension bus channel. The lines are protected with a serial resistor and there is a pull-up resistor to VCC.
29	**RST**	30	**EXT**	RST is reset line. Active Low. EXT is the external interrupt line which be raised from an extension board. Active low.
31	**VCC**	32	**VCC**	VCC 5V supply to extension boards.
33	**GND**	34	**GND**	Common ground pins.
35	**VS**	36	**VS**	Board Input voltage forward. These connector pins are primarily used by extension boards that need the high power input. Examples are H-Bridges on such a board or boards that have their power supply circuitry.
37	**VS**	38	**VS**	Board Input voltage forward.
39	**GND**	40	**GND**	Common ground pins.

The extension board connectors on the main controller boards are female connectors placed on the right hand side of the board. Male connectors are used on an extension board to connect into the main controller or a previous extension board. There are EasyEDA symbols and PCB footprints that offer the connector pins without you going through these details. The appendix contains EasyEDA symbols for the most common board dimensions with the connectors placed in the correct location. A new projects can just start with these EasyEDA symbols.

A key question is how many controller pins are available to an extension board. As said, most of the extension boards would just need the I2C bus to drive the I2C capable ICs on an extension board. However, since there might be rather complex extension boards, the IO pins needed from the controller board to the extension are many and should allow not only for digital IO but also the function blocks inside the controller. The `DIO-x` pins on the connector map to the GPIO pins of the Raspberry Pi PICO in a way that most of the controller capabilities can be used on an extension board. We will discuss this in more detail in the main controller chapter.

For even more complex extension boards, it is perhaps the better idea to combine a main board with an extension board capabilities to one monolithic board but still keep the extension connector for other not so complex extension boards to attach. As a guideline, only the first extension board will benefit from all signals coming from the main controller board. All follow on extension boards will only get the DCC signals, the interrupt and reset line, the I2C signal and the power lines.

8.7 Track Power Connectors

In addition to the extension board connector, there is the **track power connector**. This connector is only used by the base station, block controller and associated extensions. Its purpose is to pass the track power signals from the H-bridges on the base station or block controller (or booster) board to the extension boards. This connector is described in more detail in the base station and block controller chapter.

Table 8.4: Controller Attributes

Pin	**Name**	**Pin**	**Name**	**Purpose**
1	**DCC-SIG-B0**	2	**DCC-SIG-B0**	Bridge-0 DCC Signal "+" and "-".
3	**DCC-SIG-B1**	4	**DCC-SIG-B1**	Bridge-1 DCC Signal "+" and "-".
5	**DCC-SIG-B2**	6	**DCC-SIG-B2**	Bridge-2 DCC Signal "+" and "-".
7	**DCC-SIG-B3**	8	**DCC-SIG-B2**	Bridge-3 DCC Signal "+" and "-".

When using all four bridge signal output pairs, each each output pair is rated up to 3Amps. For high power bridges with up to 6Amps, two pairs can be combined and the number of bridges signals passed on is two.

8.8 Summary

This chapter introduced the basic ideas behind a hardware module, it connectors and board layout. A key concept is the idea of a common component, the main controller, and extensions that can be connected. Nevertheless, there are good cases for combining a main controller and the extension hardware into one monolithic board. But in any case, the connectors and their purposes stay the same from board to board. While the main controller boards always have the LCS bus and power input on the left side, the extension connector and track line connector on the right, extension boards come in two flavors.

The first extension board type has male connectors for track line and extension lines on the left side of the board while the second type has not. Both types have female track line and extension line connectors on their right. The first type can just be plugged into the main controller type boards, additional extension boards are simply plugged into the previous extension board. The second extension type is intended for a backplane type design where main controller boards as well as up to four extension board types are plugged into a backplane board. Throughout the chapter to come, you will see how easy boards can be combined using the two connectors lanes and standards behind them.

Ready for the first hardware work ? All aboard, the train leaves for the next chapter.

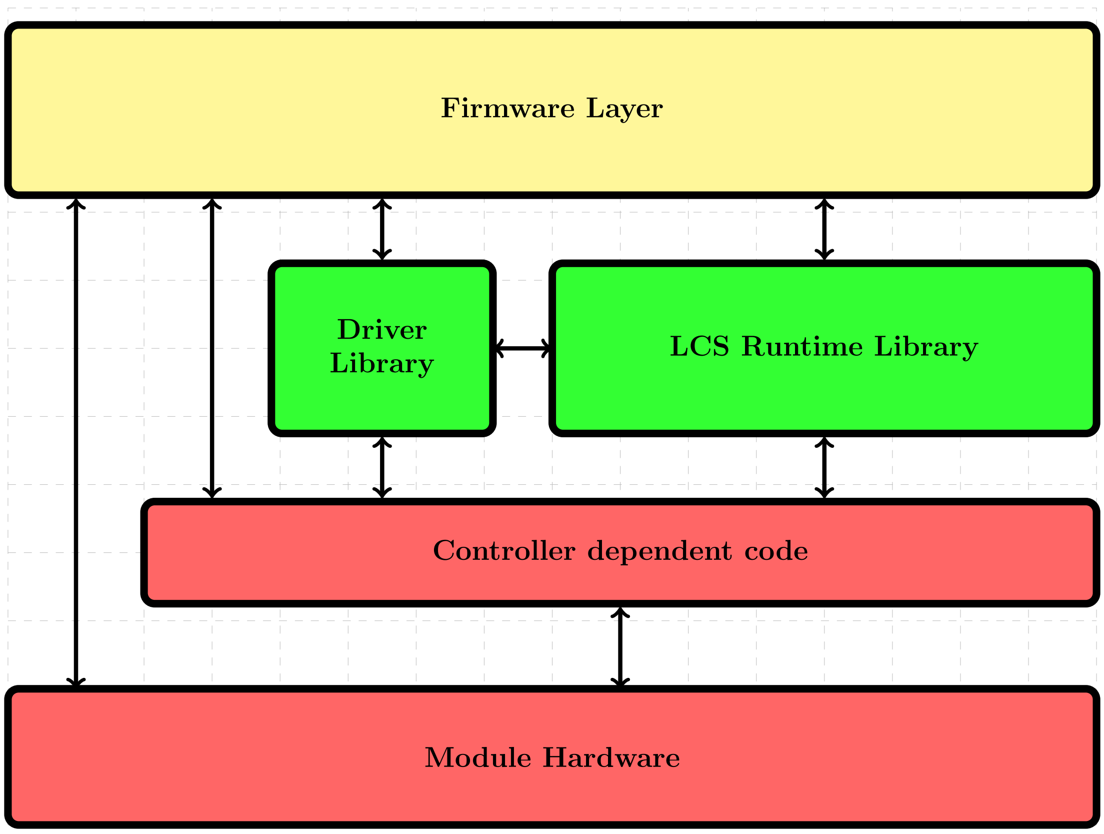
9 Controller Dependent Code

??? rework the text ... extend it...

Enough software talk ? Well not quite. The previous chapter presented the main controller boards and the extension concept. A main controller board features the controller itself, the CAN bus interface, the non-volatile memory and the extension connector with several IO pins of the controller assigned to it. During board initialization the controller hardware needs to be mapped to the actual board. Two processor versions of the main controller board were presented. It can be easily seen that different controller and board versions would place a great configuration and perhaps conditional compile burden on the LCS core library. To address this problem, there is a hardware layer library at the very bottom of the architecture that isolates the controller dependencies.

9.1 The big picture

The figure depicted below shows the refined overall structure of the node firmware. There is the core library discussed in a previous chapters and a new layer, which is the **controller dependent code layer**. The layer essentially encapsulates the required controller functions, such as a timer or a digital I/O pin, and offers a common interface to core library and firmware layer that directly uses the controller functions. The picture also shows a component labelled "extension driver". An extension driver is piece of software that knows how to handle an extension board. We get this this part later when we talk about more about extensions.



Using the CDC layer does not mean that access to the bare bones controller chip is not possible. Any controller HW function can be accessed directly at the expense of that the code will most likely not be portable between different controller families. Still, here may be good reasons for the direct path. The following sections describe will now what the CDC library is offering across all controller platforms.

9.2 Configuring the pins

The CDC library is rather low level hardware abstraction to give access to the pins which will work for the Atmega family and the Raspberry PI Pico and perhaps over time other controllers as well. The key identifier to access a hardware input/output is the pin number. Using the correct pin numbers according to the hardware developed is therefore very important. At the same time the upper layer code should not deal with these details. There needs to be a mapping of actual pin numbers and functions to the controller family and the hardware developed.

Each project therefore needs to define a structure containing some constants and pin number assignments that are used through the node firmware. For this purpose, the CDC library defines a structure with all the pin names and a sensible default setting for a particular controller. Think of the structure a the superset of all pins and HW functions that can be configured for any controller. Using the structure, all the firmware programmer has to do is to set the controller pin numbers of the particular hardware module design to the names predefined in that structure. The upper layer code then just uses these names. The following figure shows the CDC configuration structure.

```

  ConfigInfo ...
```

While the whole idea of the CDC is isolating the firmware programmer from the controller layer and board revisions, the pin assignments cannot be chosen arbitrarily on all supported processor families. An application uses the default configuration routine to obtain an initialized configuration structure with controller specific values set. The application will then fill in the assigned pins and other configuration values. Note that the default configuration setting only fills in what are the controller limitations and leaves all else undefined. An application takes this initial structure and fills in what are board version specific. Throughout the life of the application, this structure is the ”single source of truth” for pins. Under their defined name all upper layers refer to the configured IO capabilities. Once all is set, the **init** configuration routine, described later, does the sanity check for the given controller family hardware. For example, on the Atmega the UART pins numbers are fixed if used. On the PICO the pin numbers can be assigned to a couple of different slots. Whatever can be checked is checked. There is however no absolute guarantee that the configuration structure is valid in any cases.

Most CDC routines use pins as one of their input argument. These arguments are not checked again at the level of the configuration validation. For performance reasons, just some quick sanity checks are performed.

For each part of the CDC library, there is a configuration routine. For example, the digital IO configuration will set a particular pin to be an input or output pin and so on. During this configuration only basic checking what a controller can support on that pin will be done. The ATmega is far more restrictive with respect to the IO pins used than the Raspberry. The CDC library will do whatever it can to do such checking. During actual usage of such a pin, i.e. the digital read or write in the example above, no further checking will take place. During initialization, the configuration structure is checked against what the controller is capable. This also includes the pins assigned to UART, SPI and I2C pins.

9.3 CDC Library setup

To the firmware programmer, the library is a set of functions in the name space CDC. A call to any of the routines typically has the form ”CDC::xxx”. Of course, the name space can be declared upfront so the prefix is not needed. The example shown below will just show the fully qualified signature. The very first thing a node firmware should do is to set up the controller dependent library. If for some reason access to the lower layer is required before the LCS library is initialized, the calls can be made directly from the node firmware. There is also a convenience routine to print the content of the configuration structure.

```

   Declaration part...
```

9.4 General Controller Attributes and Functions

The CDC layer provides a set of common low level functions. There is a function that creates a unique ID for the controller board. It is primarily used when a node needs a hardware module unique identifier. The controller internal memory and any internal EEPROM sizes return the hardware capabilities of processor and installed NVM. The NVM select pin is used for the VNVM memory SPI addressing. Finally, the CANBus controller needs to know the SPI bus select pin and the mode, i.e. baud rate and controller frequency. The library also offers the timestamp routines for milliseconds and microseconds since start.

```

   Declaration part...
```

Some of the routines can also be found in the Arduino IDE and its libraries for the Arduino. As this project perhaps may also be implemented in an non-Arduino environment, this dependency is also hidden behind the CDC layer.

9.5 Power Fail detect

The main controller board features optional power failure detection. The power supply provides a signal line to the controller which goes low when power drops. The power fail input pin is set in the configuration structure and just passed as an input to the configure routine.

// ??? has changed...

9.6 External Interrupt

The CDC library offers a set of routines for handling an external interrupt. While a controller typically allows for interrupts on almost any IO pin, there are one some controllers dedicated IO pins which offer an interrupt input with flexible setting and high resolution timing. A callback needs to be registered for this interrupt.

// ??? has changed ...

9.7 Status LEDs

The main controller board features two LEDs. They are the ready and the activity LED. They are accessed via the **writeDio** routine. The LCS core library will use the ready LED to indicate that the node is ready. The activity LED is used to show library activities such as receiving a LCS message. The recommended colors for the LEDs are a green for the READY LED and yellow for the ACTIVE LED. The following just shows an example how to control the LEDs.

// ??? this is done via nodeControl calls ...

9.8 Timer

Although the LCS core library itself does not make use of a timer, having a general timer with a callback routine interface is an essential component. The DCC signal generation for example makes intensive use of timers to generate that signal. The timer is a repeating timer and accepts a timer value measured in microseconds. In addition, the timer already starts again counting in parallel to the timer interrupt handler code. Finally, the timer limit, i.e. the timer when the next interrupt would occur, can be set without disturbing the already active count.

```

   Declaration part...
```

Timers work slightly different on Atmega and PICO. Nevertheless, both versions allow to set the new limit, i.e. the timer value when the next interrupt would occur, while already counting toward the limit. Care needs to be taken however to set the new limit while the counter is below this limit. If the new limit value is below the timer counter value, we have passed the limit point already and the counter would simply continue to count and wrap around before hitting the new limit. Any carefully designed timer signal is gone. Again, better be quick in the interrupt handler.

9.9 Digital IO

The digital IO routines offer an interface to plain digital input and output operations. If it is an input channel, the input can be set to active low or high input. Also, there is an option to enable the controller internal input pull-up resistor. For configured output pins, two pins can be set in pairs if supported by the actual hardware configuration, i.e. the two IO pins are on the same controller output port. This feature enables the simultaneous setting the two pins. A typical use case is the DCC signal where the two signal levels are set in one call.

// ??? add the interrupt stuff...

```

   Declaration part...
```

9.10 Analog Input

Analog input configures the respective controller input ports for reading an analog value. The read method offers an asynchronous way in just starting the analog input conversion process and a hardware interrupt when the conversion completes. The registered call back is then passed the value of the conversion process. The **adcRead** function is a blocking ADC measurement call.

```

Declaration part...
```

The analog to digital converter system for the Raspberry PI PICO is compared to the Atmega really fast. A typical 12-bit conversion takes about 2 microseconds. The PICO ADC unit resolution will be scaled down to 1024 to match the Atmega resolution.

9.11 PWM Output

Depending on the controller, some digital pins can be configured with a time period and pulse width ratio. The capabilities of the underlying processor also determine what kind of PWM is possible. For example, in the main controller board Atmega1284 processor version, Timer 2 is used, allowing for two separate channels. Both channels can be set to either a fast PWM where the timer just counts up, or a phase correct mode, where the timer counts up and then down, essentially dividing the PWM period by two. Since the PWM channels are configured as two independent channels, the PWM period can only be set according to the processor clock frequency divided by the pre-scaler fixed values.

```

Declaration part...
```

The pre-scale options for the Atmega are limited to what the particular timer allows. In other words, the frequency can only be set to the nearest value of what the pre-scale option will allow. Thee PICO is again far more flexible allowing for a true frequency setting.

9.12 UART Interface

The UART interface is used to offer a serial communication channel. This is required for the RailCom feature. Currently this interface implements only an asynchronous read into a local data buffer. However, the configuration routine allows to set more parameters that are needed for the current usage. One day, even a write capability may be needed.

```

Declaration part...
```

The Raspberry PI Pico offers to implement the UART channel on one of the PIO state machines. This allows for more than the two UART blocks of the controller. The **UartMode** parameter selects what kind of UART HW is actually used.

9.13 I2C

Controller offers a serial wire IO block. The I2C will need two pins for clock and data. There is one I2C port on the Atmega1284, and two hardware blocks on the Raspberry Pi Pico. The CDC layer offers an interface to read and write a byte.

```

Declaration part...
```

9.14 SPI

SPI is the bus used for connecting NVM and CAN controller chips. The CDC library will validate that the configured pins are actually available for the SPI IO block in the respective controller. By nature, the SPI communication exchanges a data item with between two entities. A master sends a byte and in return receives a byte from the slave. To avoid surprises such as filling a buffer sent with whatever is returned from the slave, the transfer routines available will NOT overwrite a buffer sent with whatever data returned. A future version may change this behavior and offer dedicated routines to do a write or read with the transfer semantics.

```

   Declaration part...
```

9.15 Extension Connector and hardware pins

The routines described have been implemented fairly flexible and their main purpose is to shield the upper library and firmware from the controller specific implementation methods. The same routines are also used to control the pins of the extension connector. If you recall, there are two ADC channels, a digital channels and an I2C communication channel available. The first two digital pins can be overlaid with an UART interface, and the last two digital pins allow a PWM capability.

The configuration descriptor structure uses predefined names for the pins of the controller. If the hardware exports these pins via the extension connector, the connector pins can be accessed by these names. However, not all pins need to be provided to the extension connector. If for example, the digital pins DIO 0 .. 4 are used local to the board, the pins are left open on the extension connector. The only mandatory pins available on any extension connector are Power, ground, I2C, reset and E-Stop.

9.16 Summary

The controller dependent code library is the lowest layer in the LCS node software stack. Its purpose is to shield the firmware programmer from the underlying pin assignments and some of the intricacies of the particular controller. At the same time, the layer needs to be rather thin so that it adds very little to the overall path length for performance critical signal management. For special cases, there is always the possibility to access the underlying hardware directly. However, this coding my not be that portable then.

A LCS Nodes and EasyEda

The schematics and boards shown were all developed using the EasyED software. EasyEDA is a design tool for developing the schematics and PCB layouts. A PCB can then be ordered at very reasonable prices. Even during LCS node early design stages it is therefore sometimes worthwhile to just produce a PCB and avoid searching software bugs that are actually just loose connection on a breadboard. To ease the development, there are experimental boards. However when it comes to a final design, PCB boards need to be developed and ordered in larger quantitates. The LCS Node design introduced contains a main controller board and extension boards. The sizes and location of the connectors have been standardized. This appendix contains the PCB drawings of the most common LCS boards to give you a head start in developing your own boards, ensuring that all boards fit together.

A.1 Symbols and Footprints

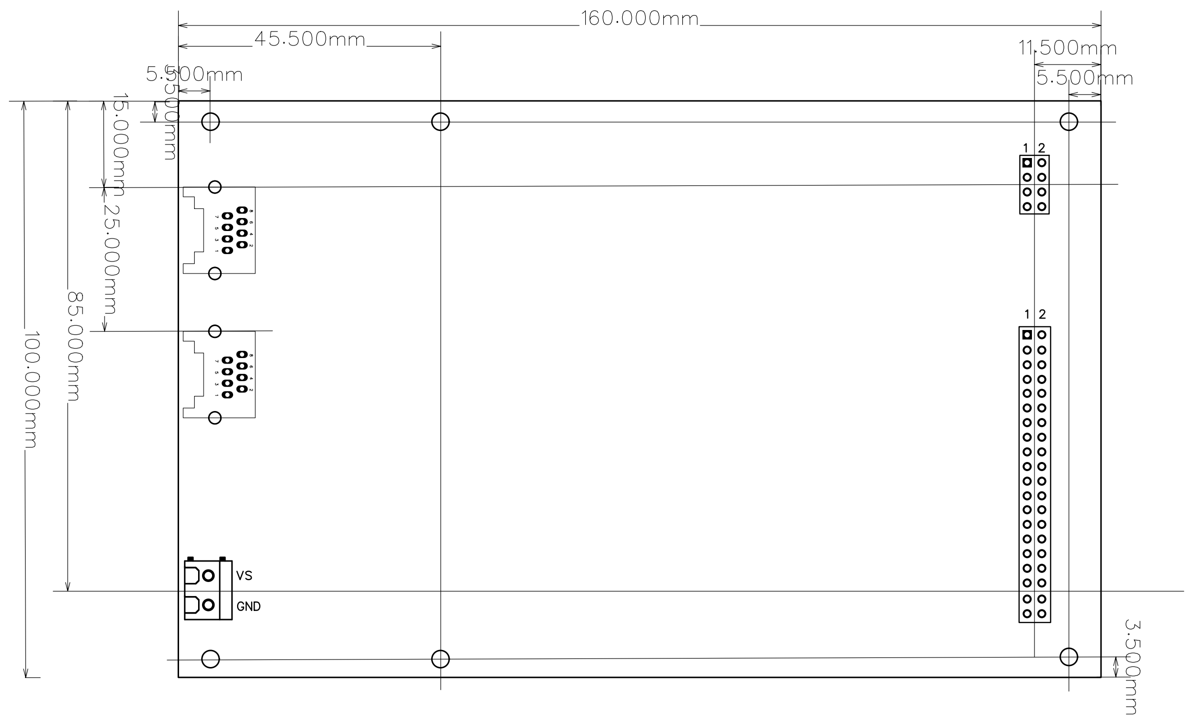
EasyEDA allows you to create symbols that represent components and can be placed in a schematic. To each symbol there should be a footprint that is used to put the component on to the PCB. The connection between the two is a list of assignments that associate a **pin** on the symbol with a **pad** on the footprint. For LcsNodes there is a list of symbols and footprints to ensure that the PCBs do have all their connectors at the exact place, so that they fit together.

A.1.1 Symbols

To ease the development of LCS boards, the entire board and its connectors are available as a symbol. Depending on the category, the symbol features the connection end points for the connectors found on the board. This symbol is associated with the corresponding footprint described in the next section. Note that the footprint needs to match the symbol. That is the number, position and meaning of the connectors found on the board map, only length of the PCB board varies.

A.1.2 Main Controller Board Footprints

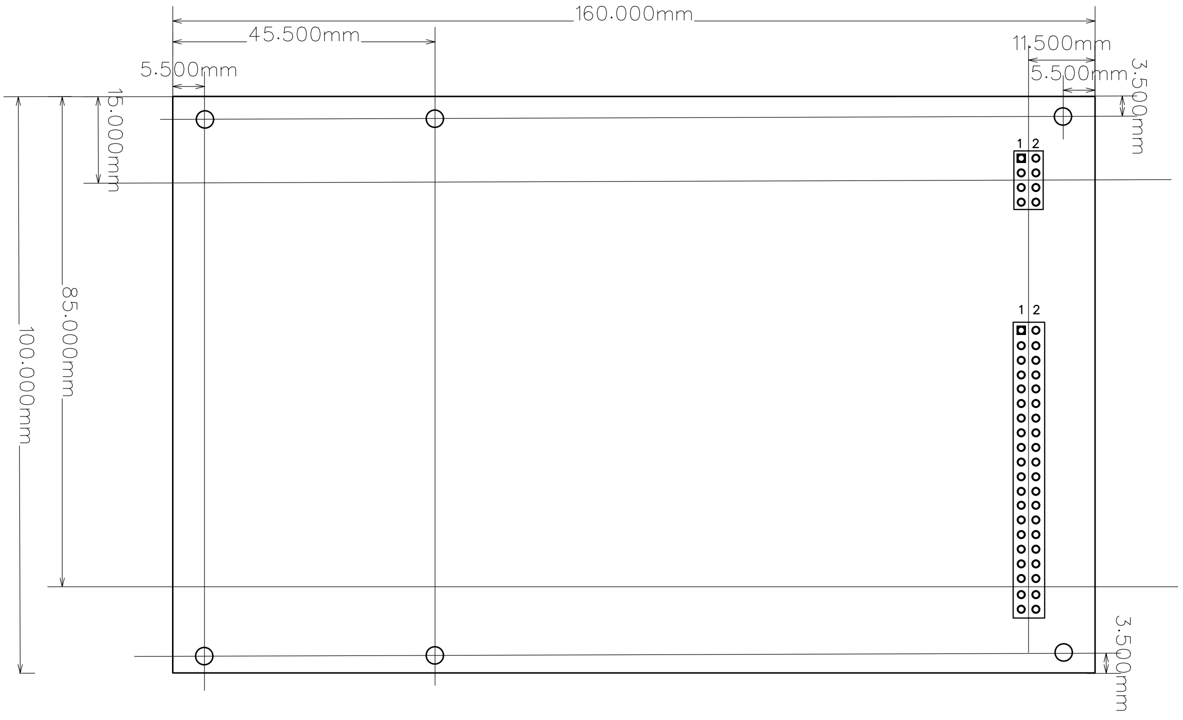
This section contains all the footprints available so far. There are three main categories. The first is anything that represents an LCS Controller portion. There are the connections to the LCS bus and the power input connector. On the left side are two connectors. The upper connector is reserved for up to four tack pow lines. Below is the LCS extension board connector. The basic LCS Main Controller Board for example is the 16cm x 10cm board shown below.

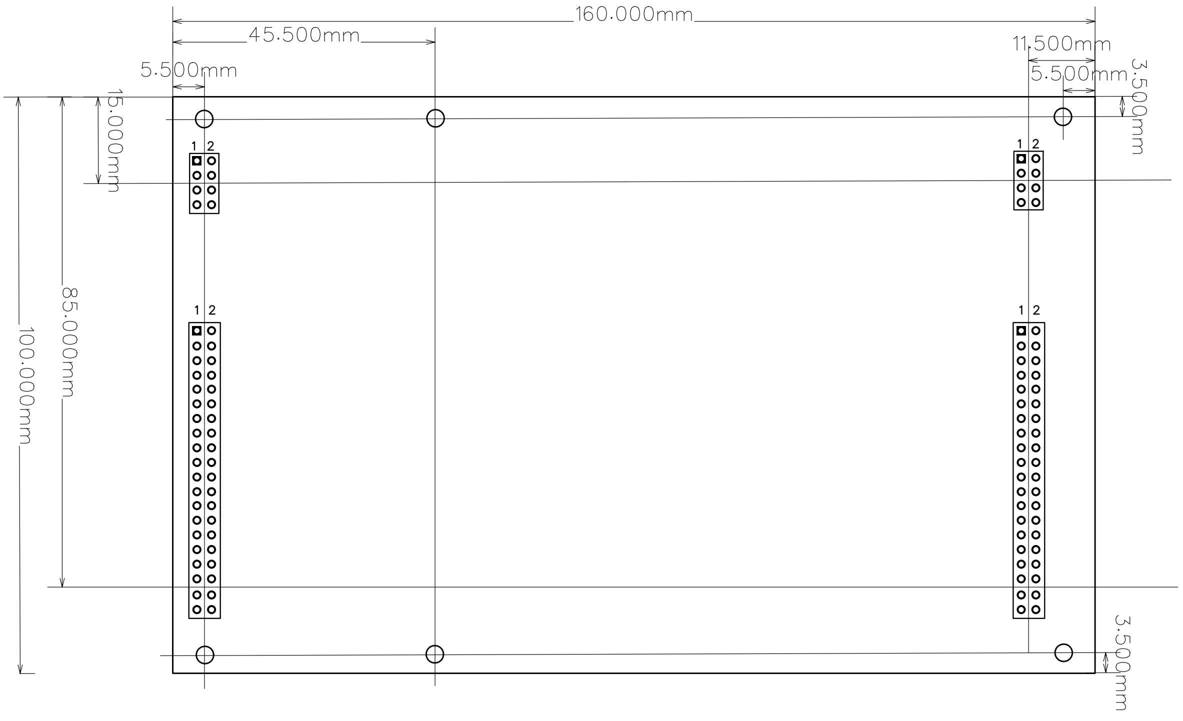


The mounting holes may look a little odd. As shown in the text to follow, there are extension boards with a form factor of 12cm x 10cm. When are the are mounted on top of the 16cm board, the holes nicely match.

A.2 Extension Boards Footprints

Next, there are the extension boards. They are straightforward and just offer the two connector lines on the right and optional on the left. Just the length varies. Boards with a connectors on the left and right are boards that can be just connected a main controller board or another extension board.


160.000mm
45.500mm
5.500mm
11.500mm
5.500mm
3.500mm
15.000mm
85.000mm
100.000mm
3.500mm
1 2
1 2


160.000mm
45.500mm
5.500mm
11.500mm
5.500mm
3.500mm
15.000mm
85.000mm
100.000mm
3.500mm
1 2
1 2
1 2
1 2

In addition to the basic 16cm x 10cm form factor, is a set of 12cm x 10cm boards. They have exactly the same layout, except that their length is 12cm instead of 16cm.

As always, there could be many more combinations as new boards with different demands are developed. Nevertheless it is important that when connectors are used, that they have the same meaning and are placed at the same location. This is the whole idea of using footprints to ensure this exact fitting.

A.3 Links

Table A.1: ...

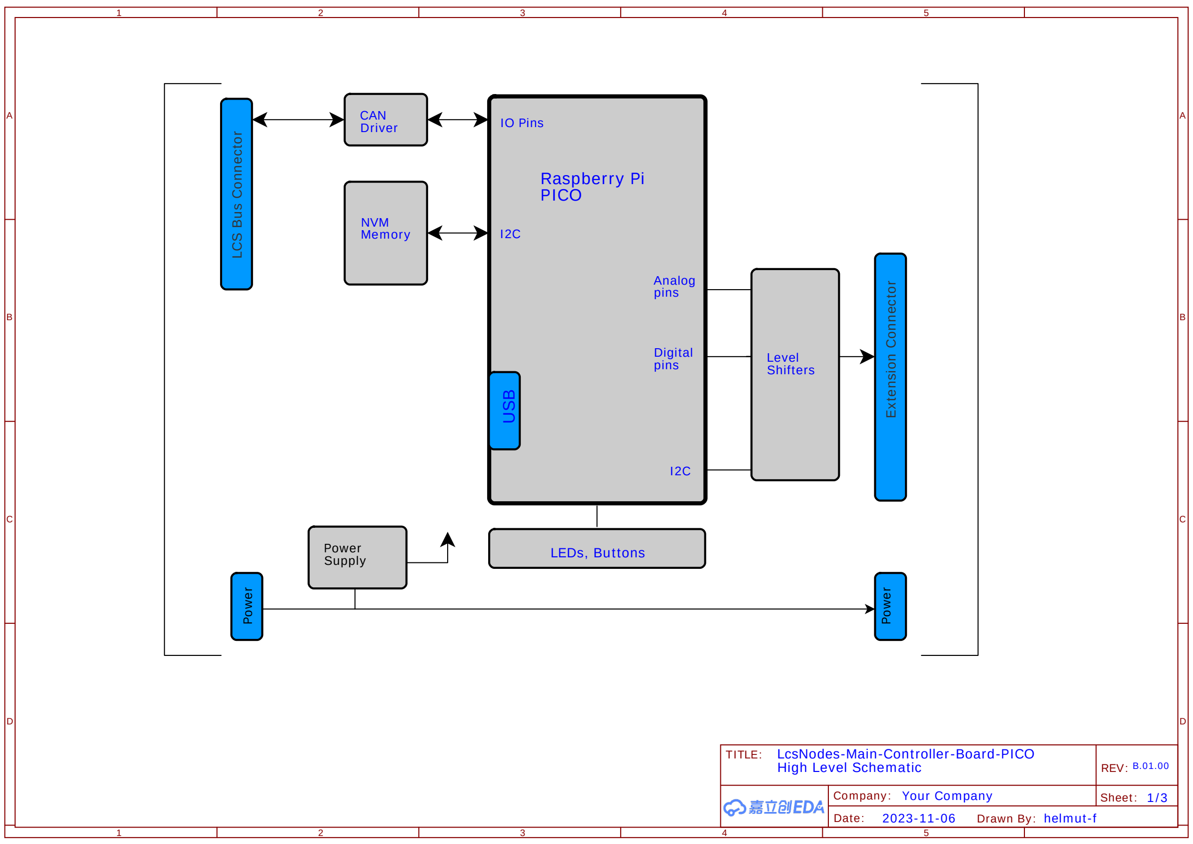
Tool	**Link**	**Comment**
EasyEDA	http://easyeda.com/de	Design tool for schematics and PCB layouts
JLCPCB	-	part of EasyEDA that manufactures PCB boards, order from within EasyEDA

B Tests

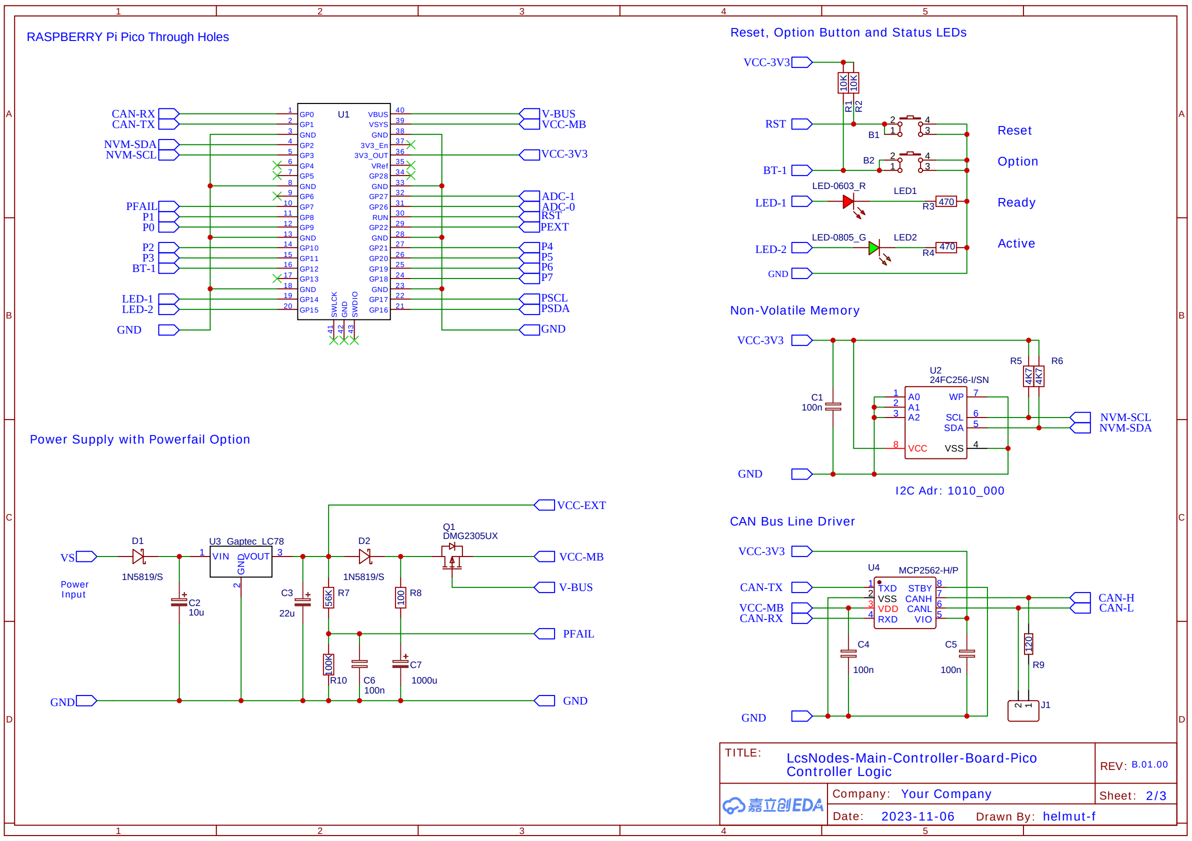
B.1 Schematics

float barrier command to ensure that text stays close to the picture but no text from after the picture.

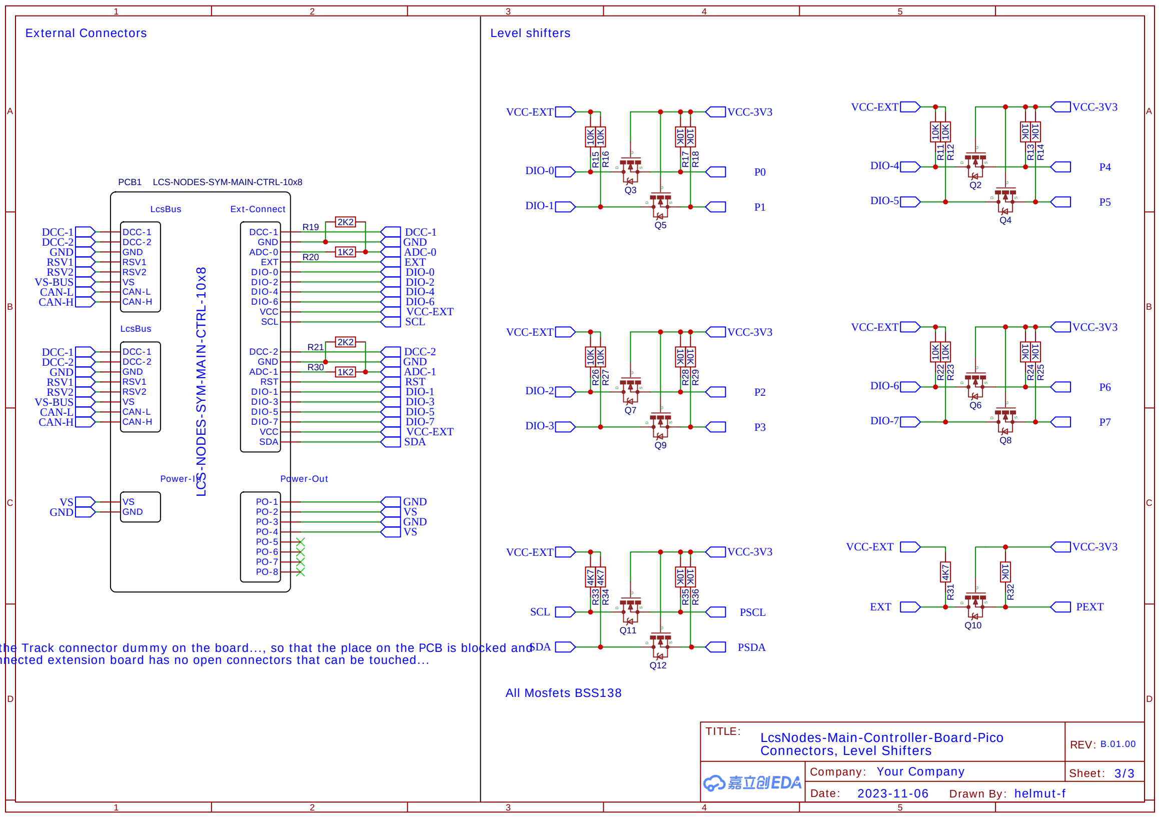
B.1.1 part 1



B.1.2 part 2


RASPBERRY Pi Pico Through Holes
Reset, Option Button and Status LEDs
Non-Volatile Memory
Power Supply with Powerfail Option
CAN Bus Line Driver
I2C Adr: 1010_000
TITLE: LcsNodes-Main-Controller-Board-Pico Controller Logic
REV: B.01.00
Company: Your Company
Sheet: 2/3
Date: 2023-11-06
Drawn By: helmut-f

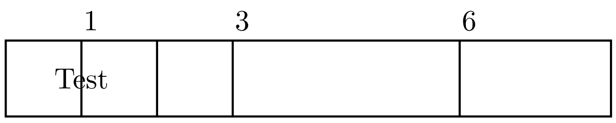
B.1.3 part 3



B.2 Pictures

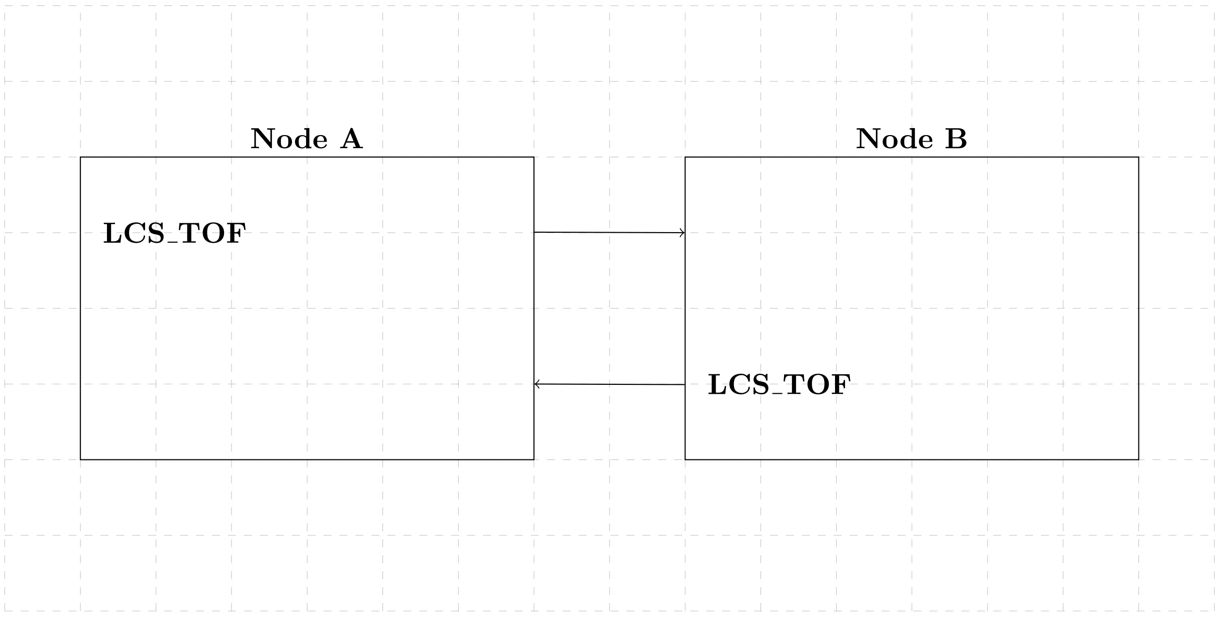
B.2.1 An instruction word layout

A little test for an instruction word layout ... will be a bit fiddling work ...



B.3 Protocol boxes

A bit cumbersome and we would need to have text at defined locations. Perhaps keep the simple table in the protocol chapter.



B.4 Split rectangle

We would need the split rectangle for the runtime area maps....