

<packt>



2ND EDITION

# Embedded Systems Architecture

Design and write software for embedded devices to  
build safe and connected systems

DANIELE LACAMERA



# Table of Contents

Preface

xi

## Part 1 – Introduction to Embedded Systems Development

1

### Embedded Systems – A Pragmatic Approach 3

|  |           |   |    |
|--|-----------|---|----|
| <b>Domain definition</b>                   | <b>3</b>  | <i>Asynchronous UART-based serial communication</i> | 12 |
| Embedded Linux systems                     | 4         | SPI   | 13 |
| Low-end 8-bit microcontrollers             | 5         | PC  | 13 |
| Hardware architecture                      | 5         | USB   | 13 |
| Understanding the challenges               | 8         | <b>Connected systems</b>                            | 14 |
| Multithreading                             | 9         | Challenges of distributed systems                   | 15 |
| <b>RAM</b>                                 | <b>9</b>  | <b>Introduction to isolation mechanisms</b>         | 15 |
| <b>Flash memory</b>                        | <b>10</b> | <b>The reference platform</b>                       | 16 |
| <b>General-purpose input/output (GPIO)</b> | <b>11</b> | ARM reference design                                | 16 |
| ADC and DAC                                | 11        | The Cortex-M microprocessor                         | 17 |
| Timers and PWM                             | 12        | <b>Summary</b>                                      | 18 |
| <b>Interfaces and peripherals</b>          | <b>12</b> |   |    |

2

### Work Environment and Workflow Optimization 19

|                          |           |                               |    |
|--------------------------|-----------|-------------------------------|----|
| <b>Workflow overview</b> | <b>20</b> | Linker                        | 21 |
| The C compiler           | 20        | Make: a build automation tool | 22 |

|  |           |                                    |           |
|--|-----------|------------------------------------|-----------|
| Debugger   | 25        | <b>Interacting with the target</b> | <b>37</b> |
| Embedded workflow                                  | 26        | The GDB session                    | 40        |
| <b>Text editors versus integrated environments</b> | <b>28</b> | <b>Validation</b>                  | <b>43</b> |
| <b>The GCC toolchain</b>                           | <b>29</b> | Functional tests                   | 43        |
| The cross compiler                                 | 29        | Hardware tools                     | 44        |
| Compiling the compiler                             | 31        | Testing off-target                 | 45        |
| Linking the executable                             | 32        | Emulators                          | 48        |
| Binary format conversion                           | 37        | <b>Summary</b>                     | <b>50</b> |

## Part 2 – Core System Architecture

### 3

#### Architectural Patterns 53

|                                 |           |  |           |
|---------------------------------|-----------|--|-----------|
| <b>Configuration management</b> | <b>53</b> | Software cryptography                        | 61        |
| Revision control                | 54        | Hardware cryptography                        | 62        |
| Tracking activities             | 55        | Running untrusted code                       | 62        |
| Code reviews                    | 56        | <b>The life cycle of an embedded project</b> | <b>62</b> |
| Continuous integration          | 56        | Defining project steps                       | 63        |
| <b>Source code organization</b> | <b>57</b> | Prototyping                                  | 64        |
| Hardware abstraction            | 57        | Refactoring                                  | 65        |
| Middleware                      | 58        | API and documentation                        | 65        |
| Application code                | 59        | <b>Summary</b>                               | <b>67</b> |
| <b>Security considerations</b>  | <b>60</b> |  |           |
| Vulnerability management        | 60        |  |           |

### 4

#### The Boot-Up Procedure 69

|                                   |           |   |           |
|-----------------------------------|-----------|---|-----------|
| Technical requirements            | 69        | Fault handlers                            | 73        |
| <b>The interrupt vector table</b> | <b>69</b> | <b>Memory layout</b>                      | <b>74</b> |
| Startup code                      | 71        | <b>Building and running the boot code</b> | <b>77</b> |
| Reset handler                     | 72        | The makefile                              | 77        |
| Allocating the stack              | 73        |   |           |

|  |           |                                    |           |
|--|-----------|------------------------------------|-----------|
| Debugger   | 25        | <b>Interacting with the target</b> | 37        |
| Embedded workflow                                  | 26        | The GDB session                    | 40        |
| <b>Text editors versus integrated environments</b> | <b>28</b> | <b>Validation</b>                  | <b>43</b> |
| <b>The GCC toolchain</b>                           | <b>29</b> | Functional tests                   | 43        |
| The cross compiler                                 | 29        | Hardware tools                     | 44        |
| Compiling the compiler                             | 31        | Testing off-target                 | 45        |
| Linking the executable                             | 32        | Emulators                          | 48        |
| Binary format conversion                           | 37        | <b>Summary</b>                     | <b>50</b> |

## Part 2 – Core System Architecture

### 3

#### Architectural Patterns 53

---

|                                 |           |  |           |
|---------------------------------|-----------|--|-----------|
| <b>Configuration management</b> | <b>53</b> | Software cryptography                        | 61        |
| Revision control                | 54        | Hardware cryptography                        | 62        |
| Tracking activities             | 55        | Running untrusted code                       | 62        |
| Code reviews                    | 56        | <b>The life cycle of an embedded project</b> | <b>62</b> |
| Continuous integration          | 56        | Defining project steps                       | 63        |
| <b>Source code organization</b> | <b>57</b> | Prototyping                                  | 64        |
| Hardware abstraction            | 57        | Refactoring                                  | 65        |
| Middleware                      | 58        | API and documentation                        | 65        |
| Application code                | 59        | <b>Summary</b>                               | <b>67</b> |
| <b>Security considerations</b>  | <b>60</b> |  |           |
| Vulnerability management        | 60        |  |           |

### 4

#### The Boot-Up Procedure 69

---

|                                   |           |   |           |
|-----------------------------------|-----------|---|-----------|
| <b>Technical requirements</b>     | <b>69</b> | Fault handlers                            | 73        |
| <b>The interrupt vector table</b> | <b>69</b> | <b>Memory layout</b>                      | <b>74</b> |
| Startup code                      | 71        | <b>Building and running the boot code</b> | <b>77</b> |
| Reset handler                     | 72        | The makefile                              | 77        |
| Allocating the stack              | 73        |   |           |

|                             |           |                                |           |
|-----------------------------|-----------|--------------------------------|-----------|
| Running the application     | 80        | Debugging a multi-stage system | 84        |
| <b>Multiple boot stages</b> | <b>80</b> | Shared libraries               | 85        |
| Bootloader                  | 81        | Remote firmware updates        | 87        |
| Building the image          | 83        | Secure boot                    | 87        |
|                             |           | <b>Summary</b>                 | <b>87</b> |

## 5

## Memory Management 89

|                                |           |                                   |            |
|--------------------------------|-----------|-----------------------------------|------------|
| <b>Technical requirements</b>  | <b>89</b> | Stack painting                    | 98         |
| <b>Memory mapping</b>          | <b>90</b> | <b>Heap management</b>            | <b>99</b>  |
| Memory model and address space | 90        | Custom implementation             | 100        |
| The code region                | 91        | Using newlib                      | 103        |
| The RAM regions                | 92        | Limiting the heap                 | 104        |
| Peripheral-access regions      | 93        | Multiple memory pools             | 105        |
| The system region              | 93        | Common heap usage errors          | 107        |
| Order of memory transactions   | 93        | <b>The memory protection unit</b> | <b>109</b> |
| <b>The execution stack</b>     | <b>94</b> | MPU-configuration registers       | 109        |
| Stack placement                | 95        | Programming the MPU               | 110        |
| Stack overflows                | 96        | <b>Summary</b>                    | <b>114</b> |

## Part 3 – Device Drivers and Communication Interfaces

## 6

### General-Purpose Peripherals 117

|                                      |            |                       |            |
|--------------------------------------|------------|-----------------------|------------|
| <b>Technical requirements</b>        | <b>118</b> | Clock configuration   | 121        |
| Bitwise operations                   | 118        | Clock distribution    | 126        |
| <b>The interrupt controller</b>      | <b>118</b> | Enabling the SysTick  | 127        |
| Peripherals' interrupt configuration | 119        | <b>Generic timers</b> | <b>129</b> |
| <b>System time</b>                   | <b>120</b> | <b>GPIO</b>           | <b>133</b> |
| Adjusting the flash wait states      | 121        | Pin configuration     | 133        |
|                                      |            | Digital output        | 134        |



|                       |     |                     |            |
|-----------------------|-----|---------------------|------------|
| PWM                   | 137 | Analog input        | 145        |
| Digital input         | 142 | <b>The watchdog</b> | <b>149</b> |
| Interrupt-based input | 143 | <b>Summary</b>      | <b>152</b> |

## 7

---

**Local Bus Interfaces** **153**


---

|   |            |                               |            |
|---|------------|-------------------------------|------------|
| <b>Technical requirements</b>             | <b>153</b> | Interrupt-based input/output  | 165        |
| <b>Introducing serial communication</b>   | <b>154</b> | <b>SPI bus</b>                | <b>167</b> |
| Clock and symbol synchronization          | 155        | Protocol description          | 167        |
| Bus wiring                                | 155        | Programming the transceiver   | 168        |
| Programming the peripherals               | 156        | SPI transactions              | 172        |
| <b>UART-based asynchronous serial bus</b> | <b>157</b> | Interrupt-based SPI transfers | 175        |
| Protocol description                      | 157        | <b>I<sup>2</sup>C bus</b>     | <b>175</b> |
| Programming the controller                | 158        | Protocol description          | 177        |
| Hello world!                              | 161        | Clock stretching              | 179        |
| newlib printf                             | 163        | Multiple masters              | 180        |
| Receiving data                            | 164        | Programming the controller    | 180        |
|   |            | Interrupt handling            | 184        |
|   |            | <b>Summary</b>                | <b>185</b> |

## 8

---

**Power Management and Energy Saving** **187**


---

|                                  |            |  |            |
|----------------------------------|------------|--|------------|
| <b>Technical requirements</b>    | <b>188</b> | <b>Measuring power</b>                           | <b>204</b> |
| <b>System configuration</b>      | <b>188</b> | Development boards                               | 204        |
| Hardware design                  | 188        | <b>Designing low-power embedded applications</b> | <b>205</b> |
| Clock management                 | 189        | Replacing busy loops with sleep mode             | 205        |
| Voltage control                  | 192        | Deep sleep during longer inactivity periods      | 206        |
| <b>Low-power operating modes</b> | <b>192</b> | Choosing the clock speed                         | 207        |
| Deep-sleep configuration         | 193        | Power state transitions                          | 207        |
| Stop mode                        | 195        | <b>Summary</b>                                   | <b>209</b> |
| Standby mode                     | 198        |  |            |
| Wake-up intervals                | 203        |  |            |

## 9

**Distributed Systems and IoT Architecture 211**

|  |            |  |            |
|--|------------|--|------------|
| <b>Technical requirements</b>                | <b>212</b> | Connectionless protocols                       | 229        |
| <b>Network interfaces</b>                    | <b>212</b> | Mesh networks and dynamic routing              | 229        |
| MAC  | 213        | <b>TLS</b>                                     | <b>232</b> |
| Selecting the appropriate network interfaces | 218        | Securing socket communication                  | 234        |
| <b>The IPs</b>                               | <b>220</b> | <b>Application protocols</b>                   | <b>237</b> |
| Standard protocols, custom implementations   | 220        | Message protocols                              | 238        |
| The TCP/IP stack                             | 220        | The REST architectural pattern                 | 238        |
| Network device drivers                       | 221        | Distributed systems – single points of failure | 239        |
| Running the TCP/IP stack                     | 223        | <b>Summary</b>                                 | <b>240</b> |
| Socket communication                         | 226        |  |            |

**Part 4 – Multithreading**

## 10

**Parallel Tasks and Scheduling 243**

|                                 |            |                                   |            |
|---------------------------------|------------|-----------------------------------|------------|
| <b>Technical requirements</b>   | <b>244</b> | Semaphores                        | 269        |
| <b>Task management</b>          | <b>244</b> | Mutexes                           | 273        |
| The task block                  | 244        | Priority inversion                | 273        |
| Context switch                  | 247        | <b>System resource separation</b> | <b>274</b> |
| Creating tasks                  | 249        | Privilege levels                  | 274        |
| <b>Scheduler implementation</b> | <b>252</b> | Memory segmentation               | 276        |
| Supervisor calls                | 252        | System calls                      | 279        |
| Cooperative scheduler           | 254        | <b>Embedded operating systems</b> | <b>282</b> |
| Concurrency and timeslices      | 255        | OS selection                      | 283        |
| Blocking tasks                  | 256        | FreeRTOS                          | 284        |
| Waiting for resources           | 262        | RIOT OS                           | 286        |
| Real-time scheduling            | 264        | <b>Summary</b>                    | <b>289</b> |
| <b>Synchronization</b>          | <b>269</b> |                                   |            |

## 11

|  |            |   |
|--|------------|---|
| <b>Trusted Execution Environment</b>               |            | <b>291</b>  |
| Technical requirements                             | 292        |   |
| Sandboxing   | 292        |   |
| TrustZone-M  | 293        |   |
| Reference platform                                 | 294        |   |
| Secure and non-secure execution domains            | 295        |   |
| <b>System resources separation</b>                 | <b>296</b> |   |
| Security attributes and memory regions             | 296        |   |
| Flash memory and secure watermarks                 | 300        |   |
| GTZC configuration and block-based SRAM protection | 301        |   |
|  |            | Configuring secure access to peripherals 302        |
|  |            | <b>Building and running the example 303</b>         |
|  |            | Enabling TrustZone-M 304                            |
|  |            | Secure application entry point 304                  |
|  |            | Compiling and linking secure-world applications 305 |
|  |            | Compiling and linking non-secure applications 306   |
|  |            | Inter-domain transitions 307                        |
|  |            | <b>Summary 310</b>                                  |
| <b>Index</b>                                       |            | <b>311</b>  |
| <b>Other Books You May Enjoy</b>                   |            | <b>322</b>  |