RPC-4000 Replica

User Guide and Building Notes

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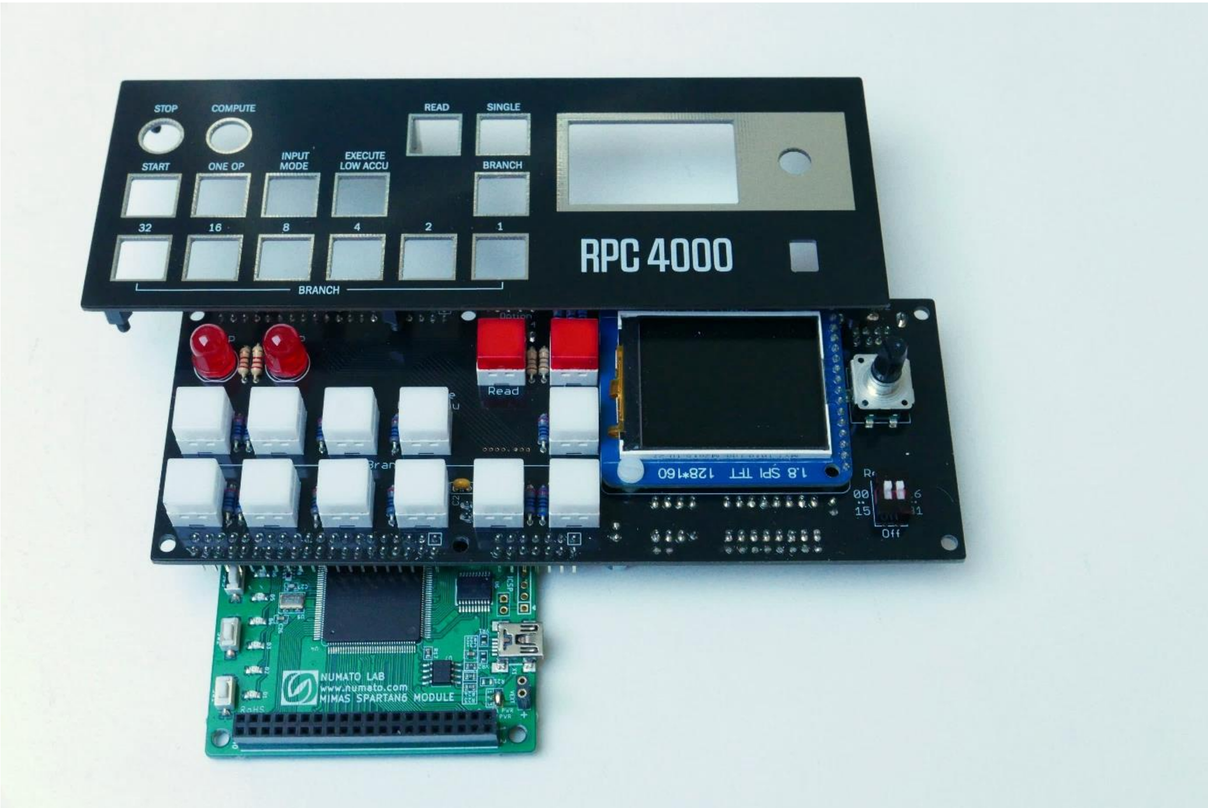
Please see www.e-basteln.de/rpc4000 for more information.



Contents

1. What's This?

The RPC-4000 computer was launched in 1960 by Royal Precision – a joint venture between office equipment specialist Royal McBee in New York and computer manufacturer Librascope (part of General Precision) in California. Building on the success of the LGP-30, it was designed around a magnetic drum, which served as the main memory and also held all CPU registers.

In contrast to the LGP-30, the RPC-4000 was not a big success in the market. The competitors had released new computers with the brand-new ferrite core memory at the same time as the RPC-4000. No longer hampered by the speed of a mechanically moving drum, and with random access to any memory cell at any time, they left the RPC-4000 behind, technologically and commercially.

So, why would one be interested in the RPC-4000? A few reasons for me:

- It is one of the last general-purpose computers designed around a magnetic drum memory. I find it fascinating to see how the developers tried to squeeze the last bit of performance out of this proven design by various tricks – only to be left way behind when core memory arrived at the scene. A look at "disruptive innovation" from the losers' side; or maybe just morbid fascination? ;-)
- The RPC-4000 reached some fame among a contemporary non-technical audience since it could compose poetry! The "Auto-Beatnik" program, developed by a research team at Librascope, was featured in Horizon and LIFE magazine. Read some sample poems, a brief report by its creator, R.M. Worthy, in the internal Librazette journal (page 2, discussing the precursor version running on the LGP-30), and its mention in the March 3, 1961 issue of LIFE magazine (pages 118-119).
- And finally: The RPC-4000 is the computer starring in the Story of Mel! A famous piece of computer folklore, celebrating the "real programmers" from the early days, preserved in the internet jargon file. I have not given up hope of finding and running Mel's original Blackjack program eventually!

This document describes a replica that is true to the bit-serial implementation and its timing, but uses modern components. The CPU is recreated in an FPGA – by implementing the complete logic equations published in the RPC-4000 service manual. The magnetic drum, while implemented in on-board memory inside the FPGA, is made tangible via an optional video display of its contents.

This way, one can play with all the quirks of the RPC-4000, including the timing behavior of programs, which depends critically on the position of instructions and data on the magnetic drum. For those who want to really dive into the details of the bit-serial design, the clock rate can be slowed down (all the way to single step, bit-by-bit clocking), and the contents of the main memory as well as CPU's transistor-based flip-flops can be inspected on the HDMI display.

This is a hobby project. I don't sell parts or kits but encourage you to build your own RPC-4000 and am happy to help with advice! All required project files are available at www.e-basteln.de/rpc4000.

Big caveat: At this time, no original software for the RPC-4000 has been retrieved. While the replica is believed to be fully functional, it will be of limited use without software!

1.1. License Terms and Credits

This document, the PCB layout and the FPGA code are Copyright © 2017-2024 Jürgen Müller, juergen@e-basteln.de. Use for commercial purposes requires my permission in writing. Use for non-commercial purposes is hereby granted free of charge, but I ask that you disclose the source and include this copyright notice. I would appreciate if you let me know when you re-use this stuff.

Use of the following third-party components is gratefully acknowledged. These may bring their own license restrictions; please check before you publish this code or use it commercially:

- USB Serial Data Transfer Core by Joris van Rantwijk, http://jorisvr.nl/usb/
- USB 1.1 PHY Layer by Rudolf Usselmann, rudi@asics.ws, http://www.opencores.org/cores/usb_phy/
- USB 1.1 PHY Layer (VHDL conversion) by Martin Neumann, martin@neumanns-mail.de, http://opencores.org/project,usb11_phy_translation
- Minimal DVI Encoder framework by Mike Field, http://hamsterworks.co.nz/mediawiki/index.php?title=Minimal_DVI-D
- TMDS Encoder by Jean P. Nicolle, http://www.fpga4fun.com/HDMI.html
- Serial UART by Ken Chapman, Xilinx Ltd, http://ohm.bu.edu/~dean/Xilinx/KCPSM6_Release7_30Sept13/UART_and_PicoTerm/UART6_User_Guide_and_Reference_Designs_29March13.pdf
- LCD font by Benedikt K., http://www.mikrocontroller.net/topic/54860

2. User Guide

This chapter assumes that you already have a working RPC-4000 replica. For building instructions, please see chapter 3, Building Notes. The following sections will guide you through the next steps to get started:

- Familiarize yourself with the real RPC-4000 – section 2.1.
- Connect a power supply to the mini-USB port in the back of the RPC-4000 replica.
  - Power requirement is +5V, 350mA.
  - Connecting to a PC which also serves as the Flexowriter terminal is the simplest setup. If you want to use RS-232 for the terminal connection, connect a separate power supply (phone charger) via USB.
- Connect an external ASCII terminal to simulate the Flexowriter – section 2.2.
- Briefly familiarize yourself with the RPC-4000 control panel and LCD – section 2.3.
- Start loading and running programs – section 2.4.

Further functions are optional and can be explored later:

- HDMI monitor for drum display – section 2.5;
- XModem file transfer to load and store drum images – section 2.6;
- FPGA update for bug fixes or enhancements – section 2.7.

2.1. The Real RPC-4000

If you have decided to build this replica, you have probably familiarized yourself with the design and operation of the original RPC-4000 to some extent. It's a somewhat obscure computer, but the manuals are available in the Bitsavers Archive, https://bitsavers.org/pdf/royalPrecision/RPC-4000/:

- The Reference Manual describes the controls and usage of the machine. Essential reading for the aspiring RPC-4000 operator!
  https://bitsavers.org/pdf/royalPrecision/RPC-4000/RPC-4000_Reference_Manual_1963.pdf

- The Programming Manual teaches the programming model, instruction set, and some practicalities including the bootstrap process and a simple boot loader.
  https://bitsavers.org/pdf/royalPrecision/RPC-4000/RPC-4000_Programming_Manual.pdf

- The Maintenance Manual teaches you more about the inner workings than you ever wanted to know. Schematics, phases and timing of the serial execution of operations, walk-through of the logic execution for each instruction… This was key to *implementing* the RPC-4000 replica but is not required reading to *use* it. https://bitsavers.org/pdf/royalPrecision/RPC-4000/RPC-4000_Maintenance_and_Training_Manual.pdf

Please check the replica project page for further relevant links and background:
www.e-basteln.de/rpc4000.

2.2. Serial Terminals

USB Interface

The **USB device** will appear on your computer as a composite device with *two* serial CDC devices. Since the RPC-4000 can address its Flexowriter and paper tape punch/reader independently, two terminal connections via USB are used to simulate these devices.

- The first device acts as the teletype (Flexowriter), the second as the paper tape Punch/Reader.
- You can open two copies of your favorite terminal program to work with both devices in parallel.
- Unfortunately the RPC-4000 replica cannot control which port numbers get assigned to the two devices on a connected PC. Depending on the USB serial devices that have been installed previously, the PC operating system assigns some available COM port numbers.
- It is not guaranteed that the teletype gets a smaller port number than the Punch/Reader! After making the first USB connection to your PC, you may need to experiment. Try the two different serial ports, or see “Controlling the Input and Output devices” in section 2.3 on how to select I/O devices via the Branch/Sense switches.

RS-232 Interface

The **RS-232 connection** can either provide a third peripheral device (e.g. to simulate an optional high-speed paper tape punch and reader) or can operate in parallel with one of the USB devices in order to connect a real, physical terminal. This is controlled via switches 1 and 2 of the 4-position DIP switch:

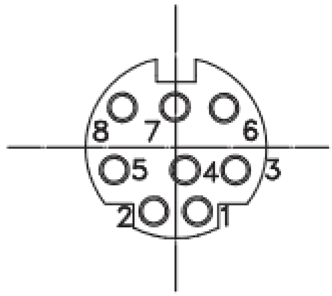
1	2	3	4	
off	off	x	x	UART not used
on	off	x	x	UART serves as auX device
off	on	x	x	UART duplicates Typewriter device
on	on	x	x	UART duplicates Punch/Reader device

The UART currently operates at a fixed speed of 19200 baud. DIP switches 3 and 4 are reserved for baud rate selection, but this is not implemented yet. In your terminal program, set the RS-232 parameters to:

- 19200 Baud, 8 data bits, 1 stop bit, no parity, hardware handshake (RTS/CTS).
- No local echo. The RPC-4000 does not normally echo the characters it receives, unless a user program is programmed to do so, or “Copy Mode” is enabled. (Long-press of READ in the replica.)

For space reasons, the RS-232 interface uses the 8-pin mini DIN jack introduced by Apple in the 1980s. The pinout used by the RPC-4000 is the same as used in the old Macintosh computers and peripherals:

Mini DIN-8 male		Sub-D 9 female	
Pin	**Signal**	**Signal**	**Pin**
1	Handshake out	CTS	8
2	Handshake in	RTS	7
3	TxD -	RXD	2
4	Gnd	GND	5
5	RxD -	TXD	3
6	TxD+	--	
7	GPIO	--	
8	RxD+	--	
		DSR – DTR	6 – 4 (bridge)



Quick Function Test

Run a terminal program on your PC, configure as indicated above, and connect to your RPC-4000. On the RPC-4000 control panel:

- Long-press SINGLE (⇧ arrow in the LCD top line will turn to ⬆),
- Press ONE OP (ONE OP and INPUT MODE will light up),
- Press INPUT MODE (no visible change),
- Press START (READ will light up).

If you type characters, they should be scrolled into the L register, second trace from the top on the LCD "oscilloscope", 4 bits at a time. You can see this on the LCD display. You should also see the characters being echoed back to the terminal program, indicating that the terminal can also receive data from the RPC-4000.

Special Characters and Control Buttons

The replica translates the Flexowriter 6-bit code to and from ASCII, for use with any modern terminal or terminal program.

The ESC key has a special function: It simulates the "Start" key on the Flexowriter, which is identical in function to the START button on the control panel.

Reading a "*" (conditional stop) character from the keyboard or from a text file also triggers a "Start" signal. In addition, it stops further input by clearing the CTS flow control signal. Input will be re-enabled by the next "Input" instruction executed by the RPC-4000.

The original RPC-4000 had various control buttons and switches on its I/O Control Panel. Many of these are unnecessary with the terminal-based implementation used in the replica; a couple are provided on the replica's main control panel. Please see "Controlling the Input and Output devices" in section 2.1 for details

Terminal Programs, Configuration and Tweaks

A real VT-100 terminal should be usable, but I recommend a terminal emulation program on a PC. These can also send and receive text files, to replace the paper tape reader and punch. If the terminal program supports the XModem file transfer protocol, this can be used to load and store complete images of the magnetic drum – see “XModem transfer” in section 2.6.

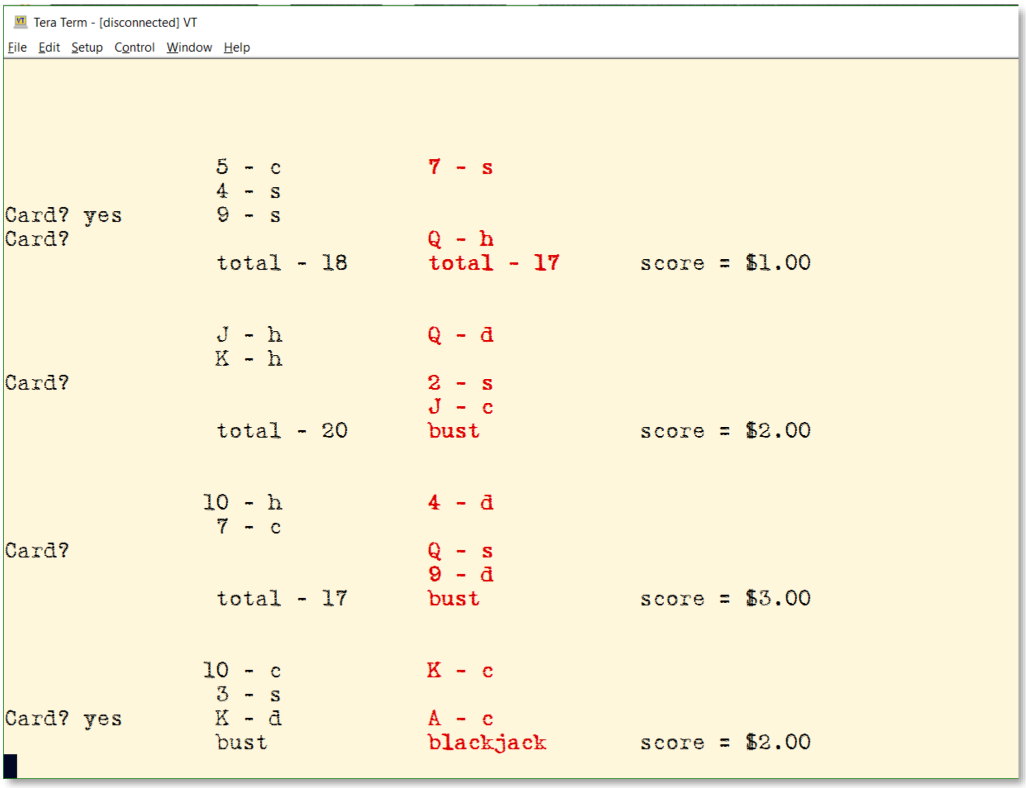
Under Windows, I like Tera Term, a free program which is still actively maintained: https://ttssh2.osdn.jp/index.html.en. If you use Tera Term, you can use some of its many configuration options to make the integration with the RPC-4000 as smooth as possible. Insert or edit the following entries in teraterm.ini:

```
; XMODEM receive command
XModemRcvCommand=\

; Black text and yellowish background colors
; for normal characters
VTColor=0,0,0,255,255,229

; Transmit delay per character (in msec)
; Workaround for Windows USB driver issue, not needed for RS-232
DelayPerChar=1
```

The Flexowriter – at least some models – had tabulator stops that were easily adjustable depending on the current application. The complete set of tab stops was arranged on a removable tabulator rack (http://homepage.cs.uiowa.edu/~jones/flexo/tour.shtml). While I am not sure whether this was the case for the Flexowriter model shipped with the RPC-4000, it appears that tab settings different from the 8-character increments common today were indeed used. For example, the instructions for the well-known Blackjack program recommend tab stop settings to make the output look right.

The VT-100 terminal has user-adjustable tab stops as well: The “ESC [3g” sequence tells the terminal to clear all pre-defined tab stops; “ESC H” sets a tab stop at the current cursor position. If your terminal program correctly emulates the VT-100, you can prepare text files to set the tabs at various positions. This will allow you to emulate the Flexowriter’s quickly exchangeable tab racks by replaying the desired tab-setting file.

Tera Term has a command line option to replay a file upon startup: "ttermpro.exe /R=tab12.tty” will start a terminal with tabs set every 12 characters, if that’s how you have set up the tab12.tty file. I have prepared such files for download at www.e-basteln.de/lgp30.



With the right color scheme, font, and tab setting, the terminal does a credible job at conveying the Flexowriter look. This screenshot shows the output from the LGP-30 version of Blackjack. The red/black color shift was not available in the RPC-4000.

2.3. Control Panel

RPC-4000 Control Panel

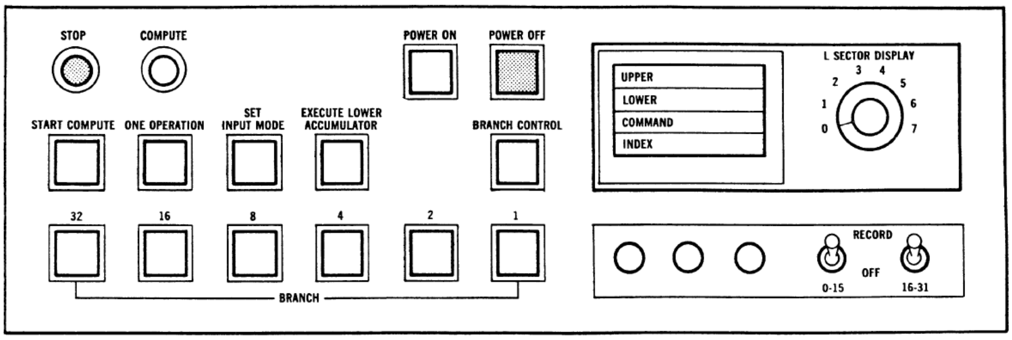
The control panel closely replicates the original RPC-4000 controls, but with some extra (overloaded) functionality:

- The colors chosen for the buttons and LEDs match the original RPC-4000 flyers and are consistent with early black-and-white marketing photographs of the machine. But it seems likely that one or more different color schemes were also in use.
- All buttons on the replica are momentary switches. Where the original RPC-4000 used latching switches, their behavior is replicated via the built-in LEDs; an illuminated LED indicates an active (depressed) switch.

  This leads to a minor difference for the EXECUTE LOWER ACCUMULATOR switch:
  In the original RPC-4000 it lights up when it is usable, i.e. in ONE OPERATION mode.
  In the replica it only lights up when activated (latched).
- The Power On/Off buttons in the upper right are not present. Two switches which originally reside on the separate I/O Control Panel take their place – READ and SINGLE CHARACTER MODE. Please see the section on “Controlling the Input and Output devices” below for details.

- Below the rotary knob, set back behind the front panel, are two write-protect switches for tracks which were commonly used for system programs like the boot loader. The two small slide switches behave exactly as in the original RPC-4000:
  - Left switch controls tracks 0..15
  - Right switch protects tracks 16..31
  - Move the switch DOWN to protect the tracks, UP to allow write access.

- Various buttons have additional functions when pressed for a longer time (0.5 seconds):
  - READ: Enable “copy mode” (local echo) for currently active I/O device.
  - SINGLE: Save drum image to on-board EEPROM
  - BRANCH SENSE 1, 2, 4: Select any combination of currently active output devices.
  - BRANCH SENSE 8, 16, 32: Select one currently active input device



Rotary Encoder

The rotary encoder has multiple functions:

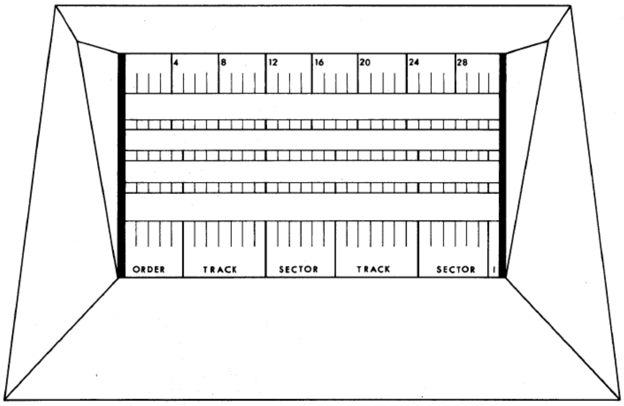
- Pushing and releasing the button will cycle through
  - Select the Lower accumulator shown on the LCD (original RPC-4000 functionality),
  - clock rate selection,
  - horizontal scrolling of HDMI drum display.

- The accumulator number (L0..L7) or the clock rate will be highlighted in the top line of the LCD when the respective parameter is controlled by the encoder. When the encoder controls HDMI scrolling, small arrows will be displayed on the HDMI screen (in the upper left and right corners).

- Horizontal HDMI scrolling will be disabled at very slow clock rates (250 Hz and below), where the drum will move in real time on the HDMI display.
- At any time, rotating the encoder *while holding the button down* will scroll the HDMI display vertically. (The RPC-4000 has twice the number of drum tracks vs. the LGP-30 – too much to fit on the screen at once. Being able to shift up and down without permanent mode change seems helpful.)
- The clock rate can be adjusted between 1.25 Hz and 1.25 MHz. The original speed is approx. 125 kHz. Rotate further left from 1.2 Hz to enter single-step mode, where the drum stops and each encoder step to the left moves it by a single bit position.

LCD Display

The LCD mainly shows the original RPC 4000's oscilloscope traces (in green) and the printed scale overlay (in grey). The order of registers is the same as in the original:



UPPER ACCUMULATOR
LOWER ACCUMULATOR
COMMAND REGISTER
INDEX REGISTER

In addition, the top line shows status indicators which are not present in the original RPC-4000. From left to right:

- Current clock rate (inverted when controlled by the encoder),
- Active input and output devices (this replaces the separate control unit of the original RPC-4000; details below),
- Lower Accumulator currently selected for display (inverted when controlled by the encoder). This replaces the pointer on the rotary switch in the original RPC-4000.

Controlling the Input and Output devices

In the original RPC-4000, I/O devices are selected and controlled via a separate control panel on the tape punch/reader unit. To **select the active I/O devices**, the replica uses the top line of the display and "overloaded" breakpoint buttons instead:

- Active Input devices are shown behind the ⇩ symbol in the display.
  T = Typewriter, R = tape Reader, X = auXiliary device.
  These are controlled by long presses of breakpoint buttons 32=T, 16=R, and 8=X.
  Only one device can be active at any time, so these behave as "radio buttons".
- Active Output devices are shown behind the ⇧ symbol in the display.
  T = Typewriter, P = tape Punch, X = auXiliary device.
  These are controlled by long presses of breakpoint buttons 4=T, 2=P, and 1=X.
  Multiple devices can be active in parallel, so pressing each button repeatedly toggles its device on and off.
- The ⇩ symbol changes to ⬇ when the current input device is ready to send data to the computer (same as the READ button's LED).
- The ⇧ symbol changes to ⬆ when the current I/O device is in Copy Mode (automatically echoing each input character to the output device).

Two switches in the upper right of the front panel control the **operating mode of the input device**. Their functionality normally resides on the control panel of the punch/reader unit:

- READ is a toggle switch which replaces the START READ and STOP READ buttons on the original reader/punch. When active (illuminated red), the device is active and can send characters to the RPC-4000. This also gets activated by an INPut instruction.
- SINGLE is the SINGLE CHARACTER MODE switch. In Single Character Mode all characters enter the computer, and a START signal is sent after each character. In Normal Mode (SINGLE not illuminated) only character codes 16 to 62 are sent to the computer, and a START signal is only sent when the Stop code (*) is detected or the START button is pressed. This behavior mimics the real RPC-4000; see the original Reference Manual for details.
- READ pressed for more than 0.5 seconds: Enables "copy mode" (local echo). Copy mode is indicated by turning the ⇧ symbol in the LCD to ⬆.

The **I/O control panels of the original RPC-4000** offered more control options, e.g. to copy data from one device to another (for copying or printing tapes) and to control the parity check logic. In the replica, copying of data can be handled offline on the PC, and parity checks are not implemented on the serial I/O devices. I believe that all I/O controls which are essential for developing and running programs are available on the replica – please get in touch if anything appears to be missing or not working as expected!

The RPC-4000 can also **switch between I/O devices under program control**, by outputting control codes 64..127. See the Reference Manual Appendix C (p. 35) for a listing of device selection codes.

- The replica maps the main 4500/4510 unit to its Typewriter, Punch & Reader devices.
- All other units (secondary tape/typewriter 46x0, fast tape reader 4410, punch 4440) are mapped to the auXiliary device – assuming that no application will expect more than one of them to be present.

2.4. Getting Started

To execute your first RPC-4000 instruction, entered interactively via the accumulator, take the following steps:

- Connect an HDMI monitor to the RPC-4000 replica.
- Power the replica by connecting it to a PC's USB port.
  The HDMI display and LCD should come up immediately.
- On the PC, start a terminal program and open a connection on the serial port associated with the RPC-4000 Teletype device. (First time round, you may need to open two instances and try both connections to determine which one is the Teletype and which the tape Read/Punch.)

The following operating procedures are identical in the original RPC-4000 and the replica. You can also find them documented in the RPC-4000 Reference Manual and Programming Manual (see section 2.1, "The Real RPC-4000", above).

Entering Instructions Manually

- On the RPC-4000, the Teletype should be selected as the default I/O device.
  'T' symbols should show after the ⇩ and ⇧ arrows in the top line of the LCD.
    - Long-press READ to enable Copy Mode (echo).
    - Press ONE OP to activate single-step mode.
    - Press INPUT MODE to clear the accumulator and set up an INPut instruction in the RPC-4000.
    - Press EXECUTE LOW ACCU to activate instruction loading from the accumulator.
    - Press START to start the INPut instruction.
- The READ button will light up, prompting you for input. Now you can enter your first instruction. It will be scrolled into the Lower Accumulator (L) from the LSB side, overflowing into the Upper Accumulator (U) when more than 8 digits are entered.
    - Let's try STU (Store Upper Accumulator) to track 32, sector 0:
    - Enter (without the spaces) 7654 3210 C200 0000
    - The Upper Accumulator (topmost in the display) will contain data word 7654 3210, the Lower Accumulator (just below) will contain the STU instruction C200 0000.
    - Enter '*'. This code completes the input. Since we had activated "Execute from Lower Accumulator" before, the instruction will be copied from L to the command register C.
- Press START – the instruction will be executed. The 7654 3210 data will show up in memory on the HDMI screen.
- To enter a new instruction, you will need to press INPUT MODE and then START again.

Bootstrap From Tape

Typically, new programs were loaded into the RPC-4000 from paper tape. The ROAR assembler generated tapes which started with a bootstrap sequence. Only a few manual button pushes were required to load and execute the initial instruction, which would then control the further loading of the bootstrap sequence, program loader, and user program.

The Programming Manual, starting on page 139, describes the step-by-step operation and explains the bootstrap code and a simple loader. We will just summarize the operator steps here:

▪ Press ONE Operation	ONE Op button lights up
▪ Press INPUT MODE	Lower Accumulator gets cleared (LCD), INPut instruction is loaded into Q flip-flops (HDMI)
▪ Press EXECUTE LOW ACCU	EXECUTE LOW ACCU button lights up
▪ Press START	READ button lights up; ready to receive input

- Start sending the bootstrap "tape" via your terminal program (or paper tape reader)
- Reading will stop after the first double-word has been read into U+L.

▪ Press START	First instruction is executed – writes to track 127, sector 0.
▪ Press EXECUTE LOW ACCU	Button light turns off
▪ Press INPUT MODE	Sets up another INPut instruction in the Q flip-flops
▪ Press START	READ button lights up; ready to receive input

- The remainder of the tape will be read automatically.
- Tapes should end with an instruction which jumps directly to the entry point of the newly loaded program.

Restarting a Program on the Drum

Once a program has been loaded onto the drum, it can be re-started from there, without reloading it from tape every time.

To **start a program at address zero** (track 0, sector 0), only the control panel buttons are required. Clearing the accumulator L will set up a HALT instruction in the accumulator with 0.0 as its next instruction. Executing that instruction will transfer program control to address 0.0:

▪ Press ONE Operation	ONE Op button lights up
▪ Press INPUT MODE	Lower Accumulator gets cleared (LCD), INPut instruction is loaded into Q flip-flops (HDMI)
▪ Press EXECUTE LOW ACCU	EXECUTE LOW ACCU button lights up
▪ Press START	READ button lights up; ready to receive input
▪ Press START	INPut complete, 0000 instruction gets loaded into C
▪ Press EXECUTE LOW ACCU	Button light turns off
▪ Press ONE OP	Button light turns off
▪ Press START	Execute HLT command in C, transfer control to address 0.0

To **start a program at an arbitrary address**, we need to add the step of entering the address into the accumulator. This will create a HLT instruction which specifies our desired entry point as its next instruction address:

▪ Press ONE Operation	ONE Op button lights up
▪ Press INPUT MODE	Lower Accumulator gets cleared (LCD), INPut instruction is loaded into Q flip-flops (HDMI)
▪ Press EXECUTE LOW ACCU	EXECUTE LOW ACCU button lights up
▪ Press START	READ button lights up; ready to receive input

- Enter the start address from the terminal.
  The sector number goes into bits 25..30 in RPC-4000 numbering (shifted left by 1 bit),
  the track number goes into bits 18..24 (shifted left by 7 bits).
  E.g. track 48_{dec} becomes 1800_{hex}, sector 30_{dec} becomes $3C_{hex}$, combined into $183C_{hex}$.

▪ Press START	INPut complete, instruction gets loaded into C
▪ Press EXECUTE LOW ACCU	Button light turns off

- Press ONE OP — Button light turns off
- Press START — Execute HLT command in C, transfer control to start address

Note that – in contrast to the real RPC-4000 – the replica will not automatically retain its drum contents when powered off. See section 2.6, “Storing and retrieving drum images”.

2.5. HDMI Display

Use of the drum memory display is entirely optional. The real RPC-4000 did not have such a display, and the replica can be fully used without it. But when you really want to follow the operation of the RPC-4000 on a bit level, the display will be useful.

A monitor with an HDMI input is required. (DVI inputs can be used with a cheap passive adapter.) The video output has XGA resolution, 1024*768 pixels. Hence older 4:3 monitors should work nicely, but the picture should also look fine when scaled to a higher resolution or 16:9 format.

The display shows 64 out of the 128 tracks of RPC-4000 main memory at a time. Register contents and control signal tracks are shown below the data. Track numbers are indicated on the left and right side of the screen, sector numbers on top.

The display shows a 10-word segment of each track. Low bits are shown on the right. Word boundaries and word structure are delineated by blue bands, with track, sector and opcode fields highlighted in different shades.

In normal operation, the display is static and can be scrolled left and right with the encoder knob. (Encoder must be in normal mode, not controlling the RPC-4000 clock speed or Lower Accumulator display. Small ◄► arrows in the upper left and right corners of the HDMI display indicate when the encoder controls horizontal scrolling.) Vertical scrolling across tracks is achieved by holding down the encoder knob and rotating it.

At slow CPU clock rates (250 Hz and below), the display will switch to real-time scrolling mode. A stationary column of read/write heads is shown in green, and the drum’s bit pattern scrolls across it from left to right. The active read head is indicated by a highlighted frame; during write operations this frame switches to red color.

The four dedicated write heads for the re-circulating registers are shown in red, upstream from the read heads. When register contents change, you can observe how the write head refreshes the whole track content with the same repeating pattern, by continuously re-writing what the read head sees 32 bits downstream. The additional read heads L* and U* for the accumulators, used during multiplication and in 8-word Lower Accumulator mode, are not shown.

At the bottom of the screen, the status of the RPC-4000’s electronic flip-flops is displayed and decoded. This may be of interest if you want to follow the instruction decoding step by step, at very slow clock rates or in single-step mode. In the original RPC-4000, the user could not observe the flip-flop states.

2.6. Storing and retrieving drum images

The magnetic drum of the real RPC-4000 retains its contents – main memory and registers – when the computer is stopped and shut down. After restarting the computer, a program can be resumed at the exact point it had been stopped.

In contrast, this replica stores the drum content in RAM memory; data are lost when the FPGA is powered off. To make the use of complex programs easier – e.g the ACT compiler and libraries, which have to be read from multiple tapes – drum contents can be stored and retrieved in two ways:

EEPROM storage

When the replica is powered up, it automatically loads its drum memory contents from an on-board EEPROM. If the drum contents change during operation, they are *not* automatically written back to the EEPROM. This is deliberate – so you can experiment with the RPC-4000, but restart with from a well-defined drum image next time if the results are not worth preserving.

- To store the current drum contents in EEPROM, press and hold the SINGLE button. “Save” will be briefly displayed in the upper left of the LCD, in place of the clock frequency.
- To recall drum contents from EEPROM, switch the replica off and on again.

XModem transfer

Drum contents can also be stored on the PC and retrieved from there via XModem file transfers. To use this feature, you must use a terminal program that supports the classic XModem protocol:

- Main memory (128*64 words) and register tracks (U, L, C, X) are stored.
- The classic XModem protocol is used, with 128 Byte blocks and 1-byte checksums (not CRC).
- Open a terminal connection to the device which is currently selected as the RPC-4000’s active input device. (It does not matter which *output* devices are active. It is not necessary to activate READ mode on the RPC-4000.)
- Download of the drum contents from the FPGA is triggered via the terminal program: In the terminal program, start an XModem reception. The replica will recognize the NACK control character sent by the terminal program and will automatically start the transfer. This is part of the standard XModem protocol and should work for all terminal programs that implement XModem.
- Upload of drum contents to the FPGA is also started from the terminal program. It requires sending the reserved “\” character to signal a transfer to the replica, which will then enter reception mode and send a NACK. This function of the “\” character is *not* an XModem standard feature, but a convention adopted for the RPC-4000 replica only.

  The “\” can either be sent manually from the terminal program; in this case the upload must be started max. 100 seconds afterwards. Alternatively, some terminal programs are configurable to send an XModem upload command automatically. See “Terminal Programs, Configuration and Tweaks” in section 2.2 for an example configuration for the Tera Term program.

Data file format:

As long as you just store and retrieve drum files, you don’t need to care about the data file format. Here it is anyway.

- Data files are 33,792 byte binary files.
- First 32,768 bytes are the main memory data:
  Track 0..127 in ascending order;
  each starting with sector 00, followed by sectors in physical order; low byte first.

- Following 1,024 bytes are the register data:
  Tracks U, L, C, X in this order,
  each starting with sector 00, followed by sectors in physical order; low byte first.
- The RPC-4000 has no sector interleaving, so logical and physical word order within the tracks are the same.

2.7. FPGA Updates

The logic configuration of the FPGA can be reprogrammed if updates or bug fixes become available. You will need a PC running Microsoft Windows to do this.

- If updated configuration files become available, they will be provided for download at www.e-basteln.de/rpc4000.
- Connect the RPC-4000 replica to the PC via USB – not instead of using the regular Mini-USB connector in the back of the replica, use the connector on the FPGA board, on the bottom of the replica.
- The "Configuring the FPGA" section in the building instructions (chapter 3.3) describes how to download, install and use the small PC program which can transfer binary files to the FPGA board.

3. Building Notes

3.1. Parts

- All required components are listed in the BOM (appendix of this document), except for mechanical mounting parts. See the “Mounting” section below for comments on mounting hardware.
- All parts are available from standard distributors like Mouser, except for the FPGA and display modules.
- The Numato Mimas (Spartan 6) FPGA module is available directly from the manufacturer, Numato.com. Shipment from India via DHL has worked smoothly for me several times. I have not tried the resellers on Amazon and ebay.
- The display KMR-1.8 SPI, 128*160 pixels, comes in slightly different versions. Be sure to get the version with SPI interface and a single row of pins, as pictured here.

3.2. PCB Assembly

Assembly of the RPC-4000 PCB is mostly straightforward. Just a few notes:

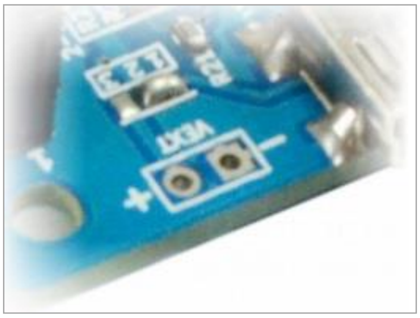
- Prepare the LCD display.
    - It will be powered by 5V, so its on-board 3.3V regulator needs to be active. Jumper JP1, near the GND and VCC terminals on the pin header, needs to be **open**.
    - I removed the SD card slot from the bottom of the LCD, for the lowest mounting profile. If you do not have a hot air soldering station, this can be done destructively with a conventional soldering iron: Unsolder the two tabs at the SD card cage’s front edge; slightly bend up the sheet metal enclosure; unsolder the two tabs at the back; repeatedly bend up further to break off all the signal connections; unsolder the left-behind pins from their pads to clean up.
- The LCD, encoder, and 2x DIP switch are mounted on top of the PCB and will jointly determine the height of the front panel. A test fit of these components, the OMRON switches, and the spacers you intend to use between the PCB and the front panel, is highly recommended!
- I recommend soldering in the LCD without a socket, to keep its profile low.
- **Before** soldering in the LCD, be sure to install the components which sit below it on the bottom: HDMI and USB jack, and the passive components associated with the HDMI port. Inspect the solder joints carefully, especially the closely space HDMI pads, since they will be inaccessible under the LCD.

- Depending on the front panel height you settle on, the two large LEDs (compute/stop indicators) may need to sit slightly above the PCB in order to look good. Test fit and install them towards the end of the build. The front panel will support the LEDs laterally, so they can simply be spaced away from the PCB a bit without further support.

3.3. Preparing the Numato Mimas board

Power Supply Connection

The Mimas board and front-end PCB require a +5V regulated supply, with a current rating of 500 mA or more. (Up to 350 mA current consumption with an HDMI monitor connected, depending on the number of LEDs that are on.) Any regular USB port or small USB-style power supply should be adequate.



The Mimas board can be powered through its USB connector, and generates the 3.1V supply for the FPGA and most components on the RPC-4000 front end. But a few components on the RPC-4000 board require a +5V supply, which is not present on the Mimas headers P1 and P2. The required connection will be prepared in this step:

- Populate the “VEXT” connector on the Numato Mimas board with a 2-pin female header. This will mate with the single +5V pin P4 on the RPC-4000 board. The ground connection will be established via the two large headers P1 and P2.
- On the power selection solder jumper, located right behind the VEXT connector, connect all three pins with a fat solder bridge. Power can now be supplied either via USB (for testing and FPGA programming) or through an external power jack connected via the RPC-4000 piggyback board and the VEXT connector.

Attention: Do *not* supply power via USB and the VEXT connector at the same time! This would result in the two power supplies fighting over the definition of “+5V”, and could damage a power supply. If you plan to install the RPC-4000 in an enclosure with an external power jack, it’s easy to forget about this restriction if you want to connect USB for reprogramming at some point. To prevent future problems, you can change the power selection jumper later to connect pins 2 and 3 only: This will disconnect the USB power, so +5V will always have to be supplied via the RPC-4000 board, and no conflicts can occur. But for initial configuration and testing, it is more convenient to be able to use USB power.

Configuring the FPGA

To configure the FPGA with an available .BIN binary file, it is *not* necessary to install the Xilinx development environment. A simple downloading tool from Numato, the supplier of the FPGA board, is required. This tool is only available as a Windows program. You only need to perform these steps once; the FPGA will then store its configuration in flash memory:

- Obtain the .BIN file for this project from www.e-basteln.de/rpc4000.
- Download the FPGA Configuration Tool, mimasConfig.exe, from Numato: http://productdata.numato.com/assets/downloads/fpga/mimas/mimasConfig.exe

- Download the USB Driver from Numato. Unpack the ZIP file, but don't install it yet: http://productdata.numato.com/assets/downloads/common/numato_lab_usb_cdc_driver.zip
- Connect the Numato board to the PC via a USB cable.
- When prompted on the PC, install the USB driver.
- Run mimasConfig.exe, which does not require installation. Select the correct COM port (check in the device manager if unsure) and .BIN binary file, and click "Program".
- Further documentation from Numato can be found at https://docs.numato.com/doc/mimas-spartan-6-fpga-development-board/

3.4. Mounting

- There is a single mounting hole to provide additional support for the LCD, opposite the LCD's pin header. Using a Nylon screw and nut is recommended. The required spacer between the PCB and LCD will most likely be of a non-standard height; use trimmed-down plastic spacers, nuts or washers to taste.
- The Mimas board should be mounted to the main PCB with four PCB spacers. 12mm spacers work well. (You can also rely on the friction of the two 2*20 pin headers alone.)
- The front panel should be mounted to the PCB and Mimas board by six PCB spacers. 6mm spacers were slightly too short for my LCD and encoder package, so I added a plastic washer to each of them.
- The front panel does not have pre-drilled holes but has the six spacer positions marked on the bottom, matching the PCB's holes. I prefer glueing the spacers to the bottom of the front panel, to keep the look of the panel clean. Hot glue or epoxy should work.
- Alternatively, you can drill holes using the markings on the bottom of the front panel and use screws from the top. Note that one of the holes and screws will interrupt the lettering below the Branch (Sense) switches.

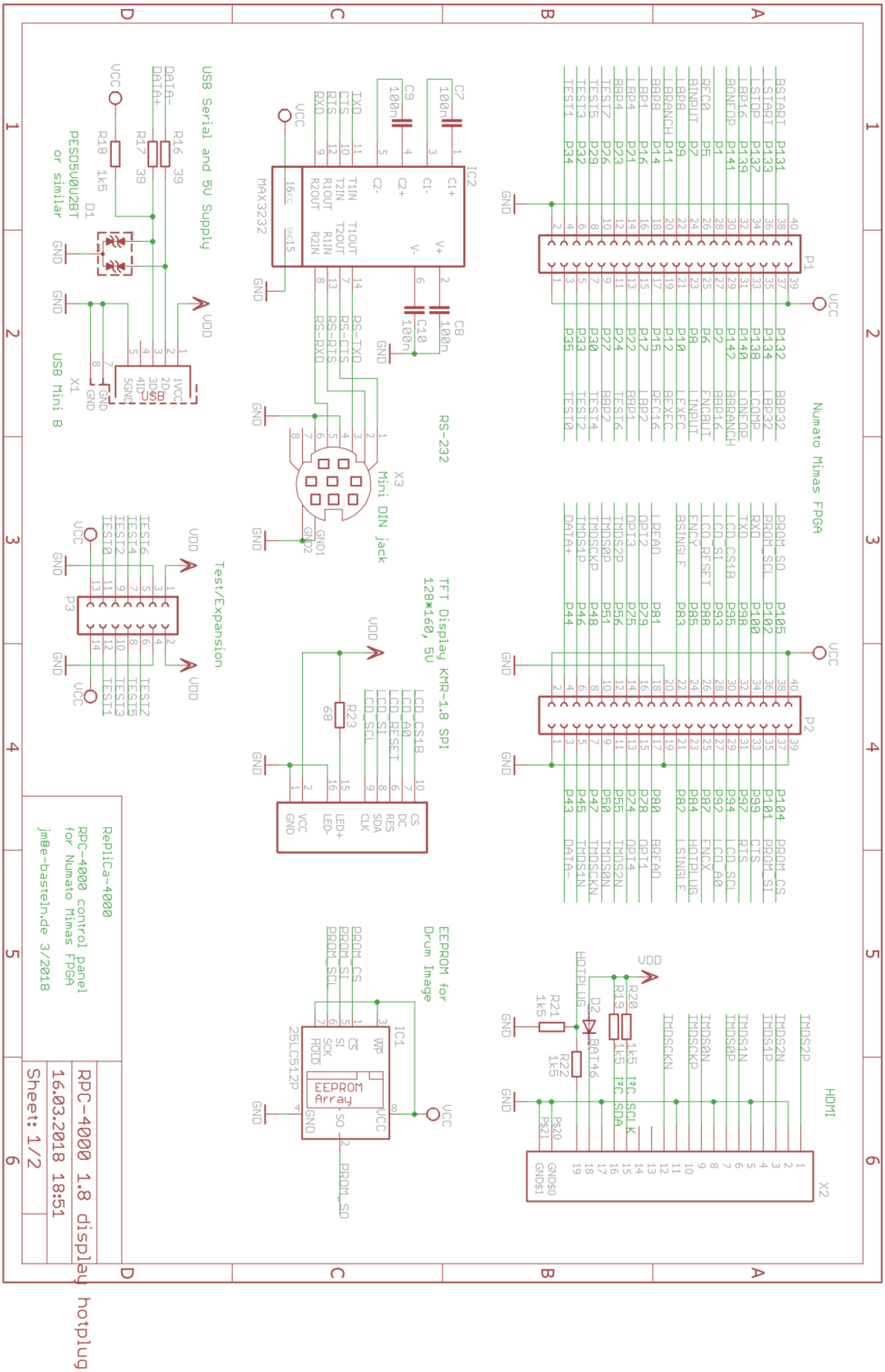
One possible mounting scheme: Black 6mm spacers at the top and bottom, with additional Nylon washers at the top. 12mm spacers between Numato Mimas and switch PCB. The black 6mm spacers have one female and one male thread, the silver 12mm spacers two female threads.

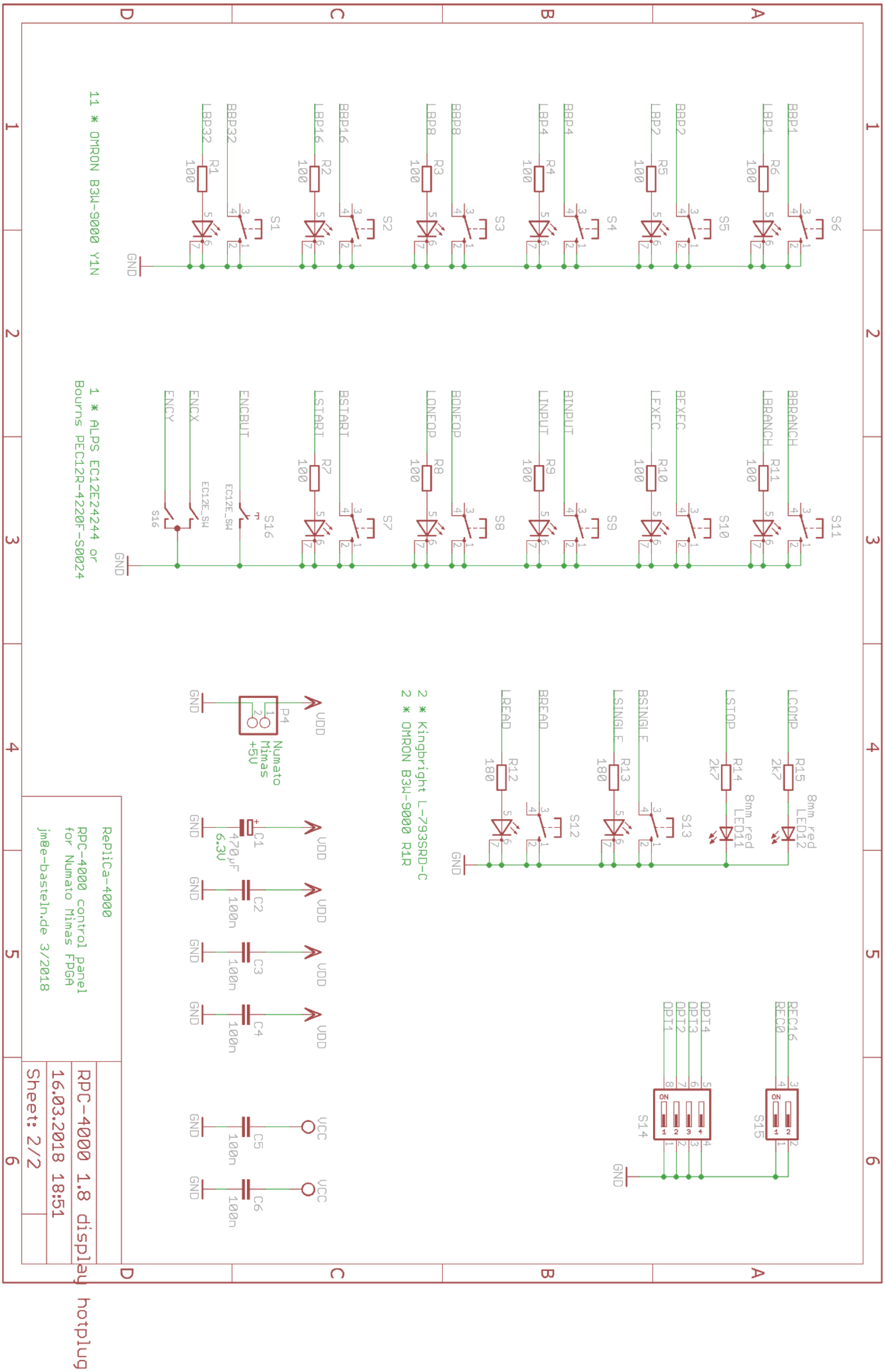
- The LCDs come mounted to their adapter PCBs with some tolerance. If your LCD is tilted or off-center vs. the cutout in the front panel, you can carefully lift it off with a knife and reposition the LCD – it is simply attached with double-sided adhesive tape. Be careful not to damage the flat cable.

4. Bill of Materials

Part	Qty	Value	Mouser part number	Comment
Semiconductors				
D1	1	PESD5V0U2BT (NXP) or similar	771-PESD5V0U2BTT/R	Dual TVS diode SOT-23, optional
D2	1	BAT46	511-BAT46	Schottky UF = 0.25V, 150 mA.
IC1	1	25LC512P, DIP-8		Serial EEPROM for drum storage
IC2	1	MAX3232, DIP-16		RS-232 level converter, 3.3V
LED11, LED12	2	Kingbright L-793SRD-C, 8mm		Dark red, matches OMRON light
Passives				
R1 - R11	11	100		all resistors 0.5W, through-hole
R12 - R13	2	180		
R14 - R15	2	2k7		
R16 - R17	2	39	594-MBB02070C3906FCT	series resistors USB
R18 - R22	5	1k5	603-MF0207FTE52-1K5	
R23	1	68		
C1	1	470µF, 6.3V	667-ECA-0JM471	electrolytic, radial, 2.54mm pitch
C2 - C10	9	100n	810-FG26C0G2A104JRT6	2.54mm pitch
Switches				
S1 - S11	11	OMRON B3W-9000 Y1N	653-B3W-9000-Y1N	10mm, 1 yellow LED, white cap. B3W-9002 also ok (higher force)
S12, S13	2	OMRON B3W-9000 R1R	653-B3W-9000-R1R	10mm, 1 red LED, red cap. B3W-9002 also ok (higher force)
S14	1	DIP switch 4x		
S15	1	DIP switch 2x		height must not exceed display and encoder!
S16	1	Rotary encoder w/ push-button	652-PEC12R-4220F-S24	ALPS EC12E24244 or Bourns PEC12R-4220F-S0024
(none)	1	Knob for 6mm flattened axis	450-AA150 + 450-CP156	knob for encoder
Connectors				
P1, P2	2	Pin header 2*20, 2.54mm pitch		I/O connection to Mimas PCB
P3	1	Pin header 2*7, 2.54mm pitch		expansion/test port
P4	1	Pin header, 1 pin		single pin, 5V from Mimas PCB
X1	1	USB jack Mini-B	538-54819-0519	angled, through-hole
X2	1	HDMI jack through-hole		3 rows, 7+6+6 pins, 1.5mm pitch
X3	1	Mini-DIN jack, 8 pins		e.g. Assmann A-DIO-FS08, Lumberg TM 0508 A/8
(none)	1	Pin socket, 2 pins, 2.54mm pitch		populate on Mimas board!
Modules				
(none)	1	TFT KMR-1.8 SPI, 128*160, 5V	(ebay)	Different variants sold! Photo in building instructions.
(none)	1	Numato Mimas FPGA module	(numato.com, Amazon)	Spartan 6. Not Mimas V2!

5. Schematics




RePliCa-4000
RPC-4000 control panel
for Numato Mimas FPGA
jm@e-basteln.de 3/2018
RPC-4000 1.8 display hotplug
16.03.2018 18:51
Sheet: 2/2
11 * OMRON B3W-9000 Y1N
1 * ALPS EC12E24244 or
Bourns PEC12R-4220F-S0024
2 * Kingbright L-793SRD-C
2 * OMRON B3W-9000 R1R