

An Embedded Operating System with a Graphical System Performance Monitor on *Raspberry* π

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1 introduction

These interactive instructions[6] follow the configuration and build of a Linux-based *operating system* (OS) for *Raspberry π* [9]. The goal of the project is a compact and deterministic OS with a running *graphical user interface* (GUI) system performance monitor application[7]. Standard *command-line interface* (CLI) tools ensure device remote access and control. The build is done with *Yocto*[11].

There are several steps organized in corresponding sections as follows. Read in Section 2 how to fetch metadata. Section 3 shows how to configure the OS build. In Section 4 learn how to build the OS image and see how to copy image to SD card in Section 5. Section 6 is dedicated to post-install issues like the configuration of the WiFi interface from the command line.

2 metadata

In current context, metadata is a set of instructions to build targets. The build configuration is managed via files with extension `conf`. They define configuration variables to control the build process.

2.1 structure

Basic concepts needed to understand metadata structure follow.

2.1.1 recipes

The instructions are organized as recipes in files with the `bb` extension. There are also files with the `bbappend` extension designed to modify recipes and `bitbake` classes with the suffix `bbclass` for instructions shared between recipes. See a full list of metadata file types in Table [2](#).

2.1.2 targets

The target may be a *software* ([SW](#)) package or group of packages. The target may also be a complete [OS](#) image.

2.1.3 layers

Metadata is organized in layers. Layers logically separate information of a project. Table [1](#) presents OpenEmbedded[[3](#)] metadata layer types.

The complete list of `github` [SW](#) metadata repositories used in this project includes *Yocto* layers, the *Raspberry π board support package* ([BSP](#)) layer, a [SW](#) layer with custom recipes including target and distribution definitions, and the build configuration itself.

layer type	contents
base	base metadata for the build
machine aka BSP	<i>hardware</i> (HW) support
distribution	policy configuration
SW	additional SW
miscellaneous	do not fall in upper categories

Table 1: metadata layer types as defined by OpenEmbedded[3]

file type	extension	purpose
recipe	bb	SW build instructions
recipe	bbappend	SW recipe modification
class	bbclass	shared instructions
config	conf	build directives
config	inc	shared build directives

Table 2: metadata file types

In short, users fetch metadata in contrast to the real data fetched later during the **OS** build. See Section 4 for details. It means that users decide where to store fetched metadata. It is nice to have all layer sub-directories in one system location. In these instructions it is referred as <META-DIR>. The second directory to create is the <BUILD-DIR>. This is where the build and the build configuration live. I suggest that <BUILD-DIR> is not inside <META-DIR> to not mix data and metadata.

2.2 meta-thc

Following the OpenEmbedded metadata classification, **meta-thc** is a **SW** layer as there are **SW** recipes. On the other hand, it is a distribution layer because it defines a new distribution based on **poky**.

See `<META-DIR>/thc/meta-thc/conf/distro/thc.conf`. In addition, there is an image recipe to build a target in `<META-DIR>/thc/meta-thc/recipes-core/images/core-image-thc.bb`.

This allows for an effective isolation of machine, distribution and image features of the [OS](#). The layer includes also shell scripts to clone metadata and to export the [OS](#) image on SD-card. These may be found in `<META-DIR>/thc/meta-thc/bin`. Learn more in following sections. See next the contents of `meta-thc`. The system location of the layer is `<META-DIR>/thc/meta-thc` by default.

```
.
bin
    burn
    metafetch
    yoctoinit
classes
    thclass.bbclass
    thconf.bbclass
conf
    distro
        thc.conf
    layer.conf
recipes-core
    dhcpd
        dhcpd_%.bbappend
    images
        core-image-thc.bb
    init-ifupdown
        init-ifupdown_%.bbappend
    thcp
        thcp
            rpip
            toprc
            wifini.sh
        thcp_0.0.1.bb
        thcp_0.1.0.bb
        thcp_1.0.0.bb
recipes-sw
    glfw
        glfw_3.3.3.bb
        glfw_3.3.8.bb
    imgui
        imgui
            imgui.ini
        imgui_0.0.1.bb
        imgui_0.1.0.bb
        imgui_1.0.0.bb
CODE_OF_CONDUCT.md
CONTRIBUTING.md
LICENSE
README
```

2.3 automation

There is a shell script to clone all metadata from public github repositories. It may serve people to build their own [OS](#) for *Raspberry π* . The script performs metadata fetch, the `bitbake` initialisation and a simple metadata verification.

```
#!/bin/sh
# name:      metafetch
# purpose:   clone rpi metadata
# code:      kaloyansen@gmail.com

FETCHER=https://github.com/
GITFETCHER=git@github.com:
BRANCH=kirkstone

LONGSFX=$(head -c 1000 /dev/random | tr -dc 'a-z')
SFX=$(expr " $LONGSFX" : ".*\(.{\3}\)")
unset LONGSFX

DEFMETADIR=$HOME/yocto/$SFX/metadata
DEFBUILDIR=$HOME/yocto/$SFX/rpi4

TARGET=core-image-thc

XNAME=$(basename $0)

say() { printf "::$XNAME:: %*\n"; }
die() { say $* && exit 0 || kill $$; }
use() {      # print options and quit

    printf "
usage:
\t $XNAME <options>
    option          \t purpose                \t default
    -h              \t print this          \t usage
    -d              \t dry run             \t wet run
    -g              \t switch to git protocol \t https protocol
    -r <branch>     \t branch              \t $BRANCH
    -m <metadir>    \t metadata directory  \t $DEFMETADIR
    -b <builddir>   \t build directory     \t $DEFBUILDIR
"
    die
}

confirm() {      # get confirmation or quit

    read -p "please confirm (y/n) " choix
    [ "$choix" = "y" ] && say confirmed || die
}
```

```

[ "$SFX" ] || die try again

while getopts "m:b:r:hgd" option; do    # parse command-line options

    case $option in

        m ) METADIR=$OPTARG;;
        b ) BUILDIR=$OPTARG;;
        r ) BRANCH=$OPTARG;;
        g ) FETCHER=$GITFETCHER;;
        d ) DRYRUN=yes;;
        h ) use;;
        * ) use;;

    esac
done

# check system path
[ "$METADIR" ] || METADIR=$DEFMETADIR
[ "$BUILDIR" ] || BUILDIR=$DEFBUILDIR
[ -d $METADIR ] || mkdir -p $METADIR || die $? cannot create $METADIR
[ -d $BUILDIR ] || mkdir -p $BUILDIR || die $? cannot create $BUILDIR
METADIR=$(realpath $METADIR) && say "metadata:\t $METADIR" || die $? cannot find
$METADIR
BUILDIR=$(realpath $BUILDIR) && say "build:\t $BUILDIR" || die $? cannot find
$BUILDIR
say "branch:\t $BRANCH"
say "protocol:\t $FETCHER"

declare -A REPO
REPO=(    # associative git repository array
    [yoctoproject/poky.git]=$METADIR/poky
    [openembedded/meta-openembedded.git]=$METADIR/oe
    [agherzan/meta-raspberrypi]=$METADIR/rpi/meta-raspberrypi
    [kaloyansen/meta-thc.git]=$METADIR/thc/meta-thc
    [kaloyansen/rpiconf.git]=$BUILDIR/conf
)

[ "$DRYRUN" ] || confirm

for repo in ${!REPO[@]}; do    # clone repositories

    command="git clone -b $BRANCH $FETCHER$repo ${REPO[$repo]}"
    say $command
    [ "$DRYRUN" ] || $command
done

[ "$DRYRUN" ] && die

# adjust bitbake layer configuration
sed -i s#/home/yocto/layer/$METADIR/g $BUILDIR/conf/bblayers.conf || die sed $?

# bitbake environment initialisation
OEINIT=oe-init-build-env
cd $METADIR/poky && pwd || die $? cannot find $METADIR/poky
[ -f $OEINIT ] && . ./$OEINIT $BUILDIR || die $? cannot find $OEINIT

bitbake-layers show-layers

echo && say "how to start a new build"

```



```
printf "  
cd $METADIR/poky  
. ./$OEINIT $BUILDIR  
bitbake $TARGET  
"
```

You may download `metafetch` [here](#). Note the associative array `REPO`. It defines the remote and local system path of repositories. The script is designed in a way that after a successful run one may start a build with `bitbake`. Do not forget to grant permissions to make script executable. It takes `<META-DIR>` and `<BUILD-DIR>` names from the command-line. You may use next examples to run `metafetch`. Running the script without command-line options like the first example results in some default configuration. You may want to specify custom directories like the second example. Otherwise the script will use default values. The default github protocol is `https` but I recommend using *secure shell* ([SSH](#)) because it is an order of magnitude faster. You may need to export one [SSH](#) public key to your github account. Use the command-line option `-g` to switch protocol. The default `git` branch is `kirkstone`. Use `-h` to see all [CLI](#) options.

```
chmod +x metafetch  
  
./metafetch  
./metafetch -m <META-DIR> -b <BUILD-DIR>  
./metafetch -g
```

3 configuration

Build configuration is in `<BUILD-DIR>/conf`, check files `local.conf` and `bblayers.conf`. *Yocto* layers are specified in `bblayers.conf`. The build directives are in `local.conf`. Variables in this file control the build. Sometimes I call these directives to avoid repetitions. To not mix them, I have isolated target [HW](#) specific directives. Two possible targets are defined in `<BUILD-DIR>/conf/raspberrypi4-64.inc` and `<BUILD-DIR>/conf/qemuarm64.inc`. The host configuration is optional. See the bottom lines in `<BUILD-DIR>/conf/local.conf` for details. Note the difference between the optional `include` and not optional `require`. The latter will interrupt the build configuration if the corresponding file does not exist.

3.1 directives

Directives control the build. It is not always easy to understand their meaning and their relations. For example, some directives change values of other directives. What is more, `bitbake` syntax is pretty complicated. In result, your life may become unbearable if the build configuration is too long. See next an alphabetical list of some important build configuration directives.

- `BB_DISKMON_DIRS` This `bitbake` variable enables free storage space verification. Users may add rules to monitor as many directories as they wish. Of course, it makes sense to add only directories on different storage partitions. The directive contains rules to trigger actions in case of low storage space during builds. Possible actions are `WARN`, `STOPTASKS` and `HALT`. Rules are defined in the following format.

```
"<action>,<directory path>,<space left>,<inodes left>"
```

- **DISTRO** This is the short name of the [OS](#) distribution. *Yocto* provides four variants of their reference distribution **poky**. See details in `<META-DIR>/poky/meta-poky/conf/distro/poky*.conf`. Some distribution dependent directive values are presented in Table [3](#).
- **DISTRO_FEATURES** Distributions can select which features they want to support through the **DISTRO_FEATURES** variable, which is set in the distribution configuration file.
- **IMAGE_FEATURES** This directive controls the contents of the [OS](#) image. Different predefined packages could be added, removed or modified via this variable. Useful examples for image features are **allow-empty-password**, **allow-root-login**, **empty-root-password**, **post-install-logging**, **splash**, **package-man** and **ssh-server-dropbear**.
- **IMAGE_FSTYPES** This is another important directive. Here I have removed archived images to decrease the built time and added the **wic** format. One may want to use the **wic** command-line tool to list the partitions on a **wic** image. See how to copy it to an SD card in Section [5](#).
- **IMAGE_OVERHEAD_FACTOR** This defines the free storage space on the **root** partition. Overhead factor of 2 means that the free space will be equal to the space already used by the [OS](#). This will double the size of the image. The default value of 1.3 increases image size with 30%.
- **INHERIT** This is a list of included **bitbake** classes. See Section [3.2](#).

- `INIT_MANAGER` The [OS](#) `init` process could be `sysvinit`, `systemd` or `mdev-busybox`.
- `MACHINE` No doubt, this is the most important directive, set here to `raspberrypi4-64`. You may want to change this value if you build an [OS](#) for a different [HW](#). If you want to emulate *Raspberry* π on your host machine with `qemu`, set `MACHINE` to `qemuarm64`. I confirm that this works although I did not find this approach very useful to test a [GUI](#).
- `MACHINE_FEATURES` This directive controls machine features. It is set in the machine configuration file and specifies the hardware features for a given machine.
- `PACKAGE_CLASSES` There are different package formats used in various Linux-based [OS](#)'s to distribute and manage programs. Both `debian` package format - `deb` and `rpm` from `RedHat` do well, but recently I had issues with `ipk` so I disabled it.
- `PACKAGE_INSTALL` This is where to specify additional [SW](#) packages. This is useful for packages not included in the image by default. In my experience, the default [OS](#) has all necessary programs or compact alternatives. However this is the directive used to append `imgui`.
- `SANITY_TESTED_DISTROS` This is a list of tested *GNU is not UNIX* ([GNU](#))/Linux distributions. Using another distribution is not prohibited, but a warning messages is generated each time `bitbake` is run. One may want to append the host machine Linux distribution to get rid of this warning. See next examples for users of `Manjaro` and `OpenSuse` rolling releases.

```
SANITY_TESTED_DISTROS:append = " manjaro"
SANITY_TESTED_DISTROS:append = " tumbleweed —"
```

config file	INIT_MANAGER	TCLIBC	status
<code>poky.conf</code>	<code>sysvinit</code>	<code>glibc</code>	fine
<code>poky-bleeding.conf</code>	<code>sysvinit</code>	<code>glibc</code>	unknown
<code>poky-altcfg.conf</code>	<code>systemd</code>	<code>glibc</code>	unknown
<code>poky-tiny.conf</code>	<code>mdev-busybox</code>	<code>musl</code>	unknown

Table 3: reference distribution configurations

- **TCLIBC** The [GNU](#) standard C library variant to use during the build. Available options are `glibc`, `musl`, `newlib` and `baremetal`.

3.2 classes

Find `bitbake` classes in `<META-DIR>/poky/meta/classes`. For example `rm_work.bbclass` defines a specific task for packages to remove intermediate files generated during the build. This decreases storage space about twice. Those who want to keep the working data and have enough storage space may comment the next line in `local.conf`.

Another class, `extrausers.bbclass`, is used with the directive `EXTRA_USERS_PARAMS` to manage [OS](#) users and passwords. In example, it may be useful to define a superuser password.

```
INHERIT:append = " rm_work"
```

4 build

It is very likely that you will need to install *Yocto* requirements[12] to be able to run `bitbake`. The list of *Yocto* sanity checked distributions currently includes poky-3.3, poky-3.4, Ubuntu-18.04, Ubuntu-20.04, Ubuntu-22.04, Fedora-37, Debian-11, OpenSUSEleap-15.3 and AlmaLinux-8.8. However, I do builds on Manjaro - a not officially supported GNU/Linux distribution - and it works fine.

4.1 requirements

Ensure that the following packages are installed.

- git
- tar
- python
- gcc
- GNU make

Find more details in *Yocto* documentation at [12]. You may need to install in addition `diffstat`, `unzip`, `texinfo`, `chrpath`, `wget`, `xterm`, `sdl`, `rpcsvc-proto`, `socat`, `cpio`, `lz4`, `gawk`, `findutils`, `crypt`, `mttools` and `inetutils`. As a double check, make sure to have the following command-line tools on your host machine: `chrpath`, `diffstat`, `lz4c`, `rpcgen`, `bash`, `bzip2`, `file`, `grep`, `patch`, `sed` and `mdir`.

The complete list of packages to install on Manjaro includes `git`, `tar`, `python`, `gcc`, `make`, `chrpath`, `cpio`, `diffstat`, `patch`, `rpcsvc-proto`.

Fetches metadata requires only 412 MB of free space. In contrast the [OS](#) build may need up to 30 GB or even 50 GB if intermediate files are kept. Read about the `bitbake` class `rm_work` in [Section 3](#).

4.2 environment

The primary build tool of OpenEmbedded based projects, such as *Yocto* is `bitbake`. To initialise `bitbake` build environment navigate to `<META-DIR>/poky` and source the initialization script like the next command.

```
source oe-init-build-env <BUILD-DIR>
```

The script changes the system path to `<BUILD-DIR>`. Next, you may want to run the following command to check project layers.

```
bitbake-layers show-layers
```

Alternatively, source the dedicated *portable operating system interface* ([POSIX](#)) script `<META-DIR>/thc/meta-thc/bin/yoctoinit`. First of all, uncomment the two lines in the script to define the system path to `<META-DIR>` and `<BUILD-DIR>`. In addition to the environment initialisation, the script defines some useful functions. Have a look at the code for details.

The target `core-image-thc` is a compact [OS](#) image with a [X](#) server and a running [GUI](#) system performance monitor[7] based on [2]. Run next command to build the [OS](#).

```
bitbake core-image-thc
```

Unless your host machine is a supercomputer, this will take at least two hours. Find a list of tasks performed by `bitbake` for a typical [SW](#) package in [Table 4](#). If a build is interrupted during a fetch task, this could be the connection with a server. A simple rerun of `bitbake` may solve this issue. If not, you may try rebuild the target responsible for the failure. See next how to do this.

task	description
do_fetch	fetch the source code
do_unpack	unpack the source code
do_patch	apply patches to the source
do_configure	source configuration
do_compile	compile the source code
do_install	copy files to the holding area
do_populate_sysroot	copy files to the staging area
do_package	analyse holding area
do_package_qa	check quality
do_package_write_rpm	deploy SW package in <code>rpm</code> format
do_package_qa	quality checks on the package

Table 4: bitbake tasks

```
bitbake <target> -c clean && bitbake <target>
```

4.3 flow

The build happens in `<BUILD-DIR>`. Table 5 presents a list of important `<BUILD-DIR>` sub-directories.

Source archives are saved in the `download` directory. They are extracted, configured, compiled and installed in the `work` directory. Built packages are stored in the `package` directory. Finally, following the build configuration packages are unpacked to create the [OS](#) image found in the `image` directory. The build flow is summarised in Table 5.

name	location	description
configuration	<code>conf</code>	build configuration files
download	<code>downloads</code>	fetched SW source code archives
work	<code>tmp/work</code>	working directory
package	<code>tmp/deploy/rpm</code>	final SW packages in <code>rpm</code> format
image	<code>tmp/deploy/images</code>	boot files, kernels and images

Table 5: bitbake workflow

5 install

The [OS](#) includes a kernel *ARM*, 64bit boot executable image of 23 MB, a *Raspberry π* configuration of Linux 5.15. This is a *long – term support* ([LTS](#)) kernel release. The total size of kernel modules is 21 MB.

Yocto provides multiple package and image formats. Different ways exist to install images on SD-card. The [OS](#) has two partitions - `/root` and `/boot`. There are no `swap` and `home` partitions.

I recommend the classic command-line tool `dd` to copy data. It works fine with different image formats like `rpi-sdimg`, `hddimg` and `wic`. The last one is recommended. Find the SD-card device name, for example `/dev/<xxx>`, unmount it with `umount` if mounted, and do copy data with the next command.

```
dd if=core-image-thc-raspberrypi4-64.wic of=/dev/<xxx> status=progress
```

- note 1: run this command in `<BUILD-DIR>/tmp/deploy/images/raspberrypi4-64`
- note 2: run this command with `root` privileges
- note 3: be careful to not specify the device name of your hard drive (see note 2)

Alternatively, there is a dedicated [POSIX](#) shell script - `<META-DIR>/thc/meta-thc/bin/burn`. Use the command-line option `-h` for details. The transfer does not take long. When it is over, replace the card to *Raspberry* π and turn it on. That's it.

6 run

Wireless connection is established via classic command-line tools like `ip`[\[1\]](#) and `iw`. The *dynamic host configuration protocol* (DHCP) client is `udhcpc`[\[1\]](#), and `wpa_passphrase`[\[10\]](#) stores WiFi connections. A dedicated [POSIX](#) shell script named `wifini.sh` is installed in `/usr/bin`, as well as a running [GUI](#) system performance monitor[\[7\]](#). The application uses Dear ImGui[\[2\]](#) library and is configured to start automatically on boot.

```
#!/bin/sh
# name: wifini.sh
# purpose: wifi connection
# code: kaloyansen at gmail dot com
# require: wpa_passphrase, wpa_supplicant, ip, iw, grep, awk
#####

# files
MYNAME='basename $0'
WPACONF=/etc/wpa_supplicant.conf
IFCONF=/etc/network/interfaces

# command-line tools
WPAPASS=/usr/bin/wpa_passphrase
IW=/usr/sbin/iw
WPASUPP=/usr/sbin/wpa_supplicant
DHCP=/sbin/udhcpc
IP=/sbin/ip

die() { echo $MYNAME $* && exit 0; }
say() { echo $MYNAME $*; }
auto() { # enable wifi connection on boot
    patch=auto\ $WIFACE
    say $patch
    grep "$patch" $1 > /dev/null || printf "
$patch
# wpa-roam $WPACONF

" >> $1;
}

[ "$USER" = "root" ] || die run with root privileges

# get wifi interface and network ssid
IWD='$IW dev'
WIFACE='echo $IWD | grep Interface | awk '{print $3}''
SSID='getopt s: $* | awk '{print $2}''

say whoami: $0

[ $SSID ] && say network: $SSID || die specify network: $MYNAME -s SSID
[ $WIFACE ] && say interface: $WIFACE || die wireless interface not found
```

```

# verify connexion
echo $IWD | grep $SSID > /dev/null && die $SSID connected || say connecting $SSID

# up interface
$IIP link show $WIFACE | grep UP > /dev/null || $IIP link set $WIFACE up

# search network
$IW $WIFACE scan | grep $SSID > /dev/null || die cannot find $SSID

FINE='grep $SSID $WPACONF'

# die debug $FINE

# 1. save network in $WPACONF
[ $FINE ] && say $SSID already configured || $WPAPASS $SSID >> $WPACONF

# 2. configure wifi to start on boot in $IFCONF
[ -f $IFCONF ] && auto $IFCONF || die $IFCONF not found

# 3. reboot
say reboot in six seconds && sleep 3
say reboot in three seconds && sleep 2
say reboot in one second && sleep 1
# yeah no kidding
reboot & die see you later || kill $$

# control files
WPASOCKET=/run/wpa_supplicant/$WIFACE

# process id files
WPAPID=/run/wpa_supplicant.$WIFACE.pid
DHCPID=/run/udhcp.$WIFACE.pid

# recreate wpa socket
rm $WPASOCKET
$WPASUPP -B -D wext -i $WIFACE -c $WPACONF || say cannot create $WPASOCKET

# start a dhcp client
$DHCP -i $WIFACE || die $?

$IIP addr show $WIFACE
$IW $WIFACE link
$IIP route show

```

The scrip may be downloaded [here](#) but it is already installed on the target OS. Specify network id from the command line with a short command-line option `-s`. See next example usage.

```
wifini.sh -s <SSID>
```

The script asks for the network password to store it encrypted for future connections. Once an *internet protocol* (IP) address is assigned to *Raspberry* π network device, the SSH server by Dropbear[5] allows for secure remote login, control and file transfer.

A client is needed to transmit mails to some *simple mail transfer protocol* (SMTP) server. Here this functionality is powered by a compact SMTP client called `msmtp`[8]. To configure user email account edit `<META-DIR>/thc/meta-thc/recipes-extended/msmtp/msmtp/.msmtp.conf` on the host machine or `~/.msmtp.conf` on the target machine. In both cases the `msmtp` configuration is performed on the target machine. Use the following command to run configuration functions, including generation of a security key, encryption of your password and the client configuration. Privacy is assured and security protected by GnuPG[4].

```
configure_mail_client
```

7 outlook

This reports the progress in the development of a custom Linux-based OS for *Raspberry* π [9]. The kernel version of this embedded OS is Linux release 5.15. A GUI system performance monitor application[7] is built as a part of the OS image. In addition, an SSH server provides remote connection, data transfer and device control.

As the OS is now functional, performance and real-time tests are ongoing. For precision measurements the OS has to be tested both on the target platform and on virtual HW via emulators, e.g. *quick emulator* (QEMU) <META-DIR>/poky/scripts/runqemu.

acronyms

BSP	<i>board support package</i>
CLI	<i>command-line interface</i>
DHCP	<i>dynamic host configuration protocol</i>
GNU	<i>GNU is not UNIX</i>
GUI	<i>graphical user interface</i>
HW	<i>hardware</i>
IP	<i>internet protocol</i>
LTS	<i>long – term support</i>
OS	<i>operating system</i>
POSIX	<i>portable operating system interface</i>
QEMU	<i>quick emulator</i>
SMTP	<i>simple mail transfer protocol</i>
SSH	<i>secure shell</i>
SW	<i>software</i>

bibliography

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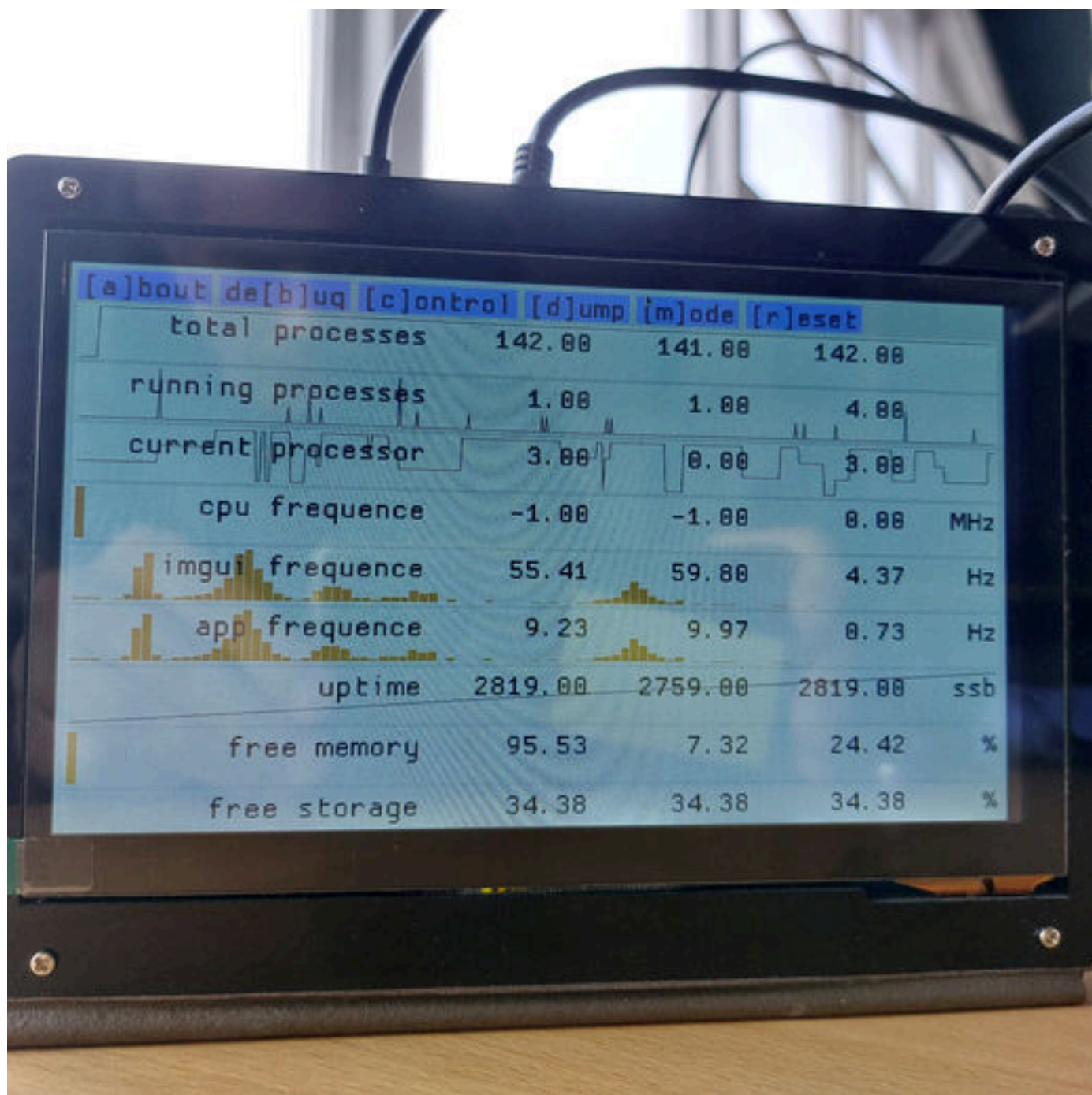


Figure 1: *Raspberry π - 4 - model B* behind a Kuman Capacitive 7" touchscreen TFT LCD module