嵌入式系統學習筆記

環境建置

安裝 GCC Toolchain for ARM

sudo apt-get install gcc-arm-linux-gnueabi

編譯 Linux Kernel

1. 下載位置 https://www.kernel.org/ (下載版本: linux-5.15.37)
2. config 配置 (使用 vexpress 預設)
   make CROSS_COMPILE=arm-linux-gnueabi- ARCH=arm vexpress_defconfig
3. make 編譯
   make CROSS_COMPILE=arm-linux-gnueabi- ARCH=arm
4. Image 位置
   arch/arm/boot/zImage

根檔案系統 rootfs

BusyBox

- 下載 busybox-1.35.0.tar.bz2
- 編譯 & 安裝

```
cd busybox-1.35.0.tar.bz2
make defconfig
make CROSS_COMPILE=arm-linux-gnueabi-
make install CROSS_COMPILE=arm-linux-gnueabi-
```

製作 rootfs

1. 創建根目錄rootfs

```
mkdir rootfs
```

2. 複製 busybox 命令到根目錄下，注意 busybox 路徑

```
cp -r busybox-1.35.0/_install/* rootfs/
```

3. 從工具鏈中複製運行庫到lib目錄下

```
mkdir rootfs/lib
cp -P /usr/arm-linux-gnueabi/lib/* rootfs/lib
```

4. 創建 4 個 tty 終端設備(c代表字符設備，4是主設備號，1 2 3 4分別是次設備號

```
mkdir -p rootfs/dev
mknod rootfs/dev/tty1 c 4 1
mknod rootfs/dev/tty2 c 4 2
mknod rootfs/dev/tty3 c 4 3
mknod rootfs/dev/tty4 c 4 4
```

5. 創建 proc, etc… 等目錄

```
cd rootfs/
mkdir -pv {bin,sbin,etc,proc,sys,usr/{bin,sbin}}
```

6. 生成 512M 大小的磁碟映象

```
qemu-img create -f raw disk.img 512M
```

7. 把磁碟映象格式化成ext4檔案系統

```
mkfs -t ext4 ./disk.img
```

8. 將文件複製到鏡像中

```
mkdir tmpfs
sudo mount -o loop ./disk.img tmpfs/
sudo cp -r rootfs/* tmpfs/
sudo umount tmpfs
```

- 如果是 Buildroot, 則將 disk.img 替換成 rootfs.ext2。

9. 建立 initial script
   此步驟把 rootfs 全部打包進 initramfs-busybox-arm.cpio.gz, qemu 啟動時只要參數加上 -initrd initramfs-busybox-arm.cpio.gz 就不需要指定 -sd disk.img

```
cd rootfs
vim init

----------------
#!/bin/sh

mount -t proc none /proc
mount -t sysfs none /sys

echo -e "\nBoot took $(cut -d' ' -f1 /proc/uptime) seconds\n"

exec /bin/sh
----------------

chmod +x init
find . -print0 | cpio --null -ov --format=newc | gzip -9 > ./initramfs-busybox-arm.cpio.gz
mv initramfs-busybox-arm.cpio.gz ../
```

QEMU

建置

To download and build QEMU 7.0.0:

```
// install essential tools
sudo apt-get install git libglib2.0-dev libfdt-dev libpixman-1-dev zlib1g-dev
// download source code
wget https://download.qemu.org/qemu-7.0.0.tar.xz
tar xvJf qemu-7.0.0.tar.xz
cd qemu-7.0.0
// config for arm/arm64
./configure --target-list=arm-softmmu,aarch64-softmmu
```

```
// build
make -j2
// install to /usr/local/share/qemu
make install
```

啟動

```
qemu-system-arm -M vexpress-a9 -m 512M -kernel zImage -dtb vexpress-v2p-ca9.dtb -nographic -append "root=/dev/mmcblk0 console=ttyAMA0 rw init=/linuxrc" -sd disk.img [-initrd initramfs-busybox-arm.cpio.gz]
```

轉存至 bash file

```
#!/bin/bash

qemu-system-arm \
-M vexpress-a9 \
-m 512M \
-kernel zImage \
-dtb vexpress-v2p-ca9.dtb \
-nographic \
-append "root=/dev/mmcblk0 console=ttyAMA0 rw init=/linuxrc" \
-sd disk.img \
-initrd initramfs-busybox-arm.cpio.gz
```

“-sd disk.img” 與 “-initrd initramfs-busybox-arm.cpio.gz” 兩者擇一即可，但使用 “-sd disk.img” 因為沒有 init 程式，啟動時會出現下列錯誤訊息：

```
can't run '/etc/init.d/rcS': No such file or directory
```

退出

```
ps -A | grep qemu-system-arm | awk '{print $1}' | xargs sudo kill -9
```

Buildroot

除了使用上述步驟建立自己的嵌入式系統模擬環境，也可以使用 Buildroot 快速建置。

版本：buildroot-2022.02.1.tar.gz

```
cd buildroot
make qemu_arm_vexpress_defconfig
make -j2
```

啟動

```
qemu-system-arm -M vexpress-a9 -smp 1 -m 256 -kernel output/images/zImage -dtb output/images/vexpress-v2p-ca9.dtb -drive file=output/images/rootfs.ext2,if=sd,format=raw -append "console=ttyAMA0,115200 root=/dev/mmcblk0" -serial stdio -net nic,model=lan9118 -net user
```

工具鍊 (toolchain) 路徑

buildroot/output/host/bin

設定 toolchain 路徑到環境變數

export PATH=$PATH:/home/hank/Workspace/embedded/buildroot/output/host/bin

編譯命令參數

make ARCH=arm CROSS_COMPILE=arm-buildroot-linux-uclibcgnueabihf-

Linux header 路徑

PC

/usr/src/linux-headers-5.3.0-64

Embedded toolchain

buildroot/output/build/linux-headers-5.15.18

Kernel 模組

新增模組

vim hank.c

```
#include <linux/init.h>
#include <linux/module.h>

MODULE_DESCRIPTION("Hank");
MODULE_LICENSE("GPL");

static int hank_init(void) {
    printk(KERN_INFO "Hello Hank !\n");
    return 0;
}

static void hank_exit(void) {
    printk(KERN_INFO "ByeBye Hank !\n");
}

// Will be invoked when insmod
module_init(hank_init);
// Will be invoked when rmmod
module_exit(hank_exit);
```

vim Makefile

```
PWD := $(shell pwd)
# 指定 linux kernel source 路徑
KERNEL_DIR = /home/hank/Workspace/embedded/kernel/linux-5.15.37
# buildroot kernel source 路徑
# /home/hank/Workspace/embedded/buildroot/output/build/linux-5.15.18

MODULE_NAME = hank
obj-m := $(MODULE_NAME).o

all:
	make -C $(KERNEL_DIR) M=$(PWD) modules
```

```
	# ARCH=arm CROSS_COMPILE=arm-linux-gnueabi-
clean:
	make -C $(KERNEL_DIR) M=$(PWD) clean
```

編譯 Module

用下面指令編譯會得到 hank.ko 與其他中間檔。

```
# 使用 sudo apt-get install gcc-arm-linux-gnueabi 工具鍊
make ARCH=arm CROSS_COMPILE=arm-linux-gnueabi-
# 使用 booldroot 工具鍊
make ARCH=arm CROSS_COMPILE=arm-buildroot-linux-uclibcgnueabihf-
```

複製模組到 rootfs

複製 hank.ko 到 rootfs 裡在重新啟動 qemu 即可在機器裡看到此模組。
複製方法可參考 ”製作 rootfs” 書籤小節的指令：8. 將文件複製到鏡像中”。

如果 qemu 使用 -initrd 啟動，則需要重新執行一次該節的指令 “9. 建立 initial script”，
產生新的 initramfs-busybox-arm.cpio.gz，才會出現在重啟的 rootfs 裡。

載入與移除模組

載入

```
insmod <module_name>.ko
```

移除

```
rmmod <module_name>.ko
```

實作 Character Driver

靜態註冊

註冊 character device

模組初始化函式中，調用 register_chrdev() 註冊字元設備，第一個參數為 major number，
若帶 0 表示由 kernel 動態分配。
hankdev_fops 為 struct file_operations 的實體變數，負責定義 driver 支援的操作函式。
最後 device_create() 負責建立裝置並掛載到 /dev 底下。如下圖：

```
# ls -l /dev/hank0
crw-------    1 root     root      248,   0 May 10 02:34 /dev/hank0
```

實作程式碼：

```
static int __init hank_init(void) {
  printk(KERN_INFO "Init Hank Module !\n");

  // register device driver with dynamic major number assigned by kernel
```

```
    major_num = register_chrdev(0, DEVICE_NAME, &hankdev_fops);

    if (major_num < 0) {
        pr_alert("[Module][%d] Registering char device failed with %d\n", current->pid, major_num);
        return major_num;
    }
    // A warpper macro for printk (linux/printk.h)
    pr_info("[Module][%d] Assign major number %d to Hank device driver.\n", current->pid, major_num);
    cls = class_create(THIS_MODULE, DEVICE_NAME);

    // create single device
    device_create(cls, NULL, MKDEV(major_num, 0), NULL, "hank%d", 0);
    pr_info("[Module][%d] Devices created on /dev/hank%d\n", current->pid, 0);

    return 0;
}
```

註銷 character device

模組移除函式中，調用 device_destroy() 移除模組初始化時建立的裝置，調用 unregister_chrdev() 註銷字元設備。

```
static void __exit hank_exit(void) {
    printk(KERN_INFO "Exit Hank Module !\n");

    // destroy single device
    device_destroy(cls, MKDEV(major_num, 0));
    pr_info("[Module][%d] Devices /dev/hank%d destroyed\n", current->pid, 0);

    class_destroy(cls);

    // unregister character device driver
    unregister_chrdev(major_num, DEVICE_NAME);
}
```

file_operations

將 file_operations 結構體的函式指標指向對應的處理函式。

```
#include <linux/fs.h>

static struct file_operations hankdev_fops = {
    .owner = THIS_MODULE,
    .read = hank_read,
    .write = hank_write,
    .open = hank_open,
    .release = hank_release,
};
```

動態註冊

註冊 character device

alloc_chrdev_region	請 kernel 動態配置 major number 給 character device driver。

cdev_init	傳入 struct cdev 與 struct file_operations 進行 driver 初始化。
cdev_add	新增 character device。

```
// alloc_chrdev_region returns 0 if success
if (alloc_chrdev_region(&dev, 0, NUM_DEVICES, DEVICE_NAME) != 0) {
    pr_alert("[Module][%d] Failed to dynamic allocate major number for device: %s.\n",
                current->pid, DEVICE_NAME);
    return -1;
}

major_num = MAJOR(dev);

cdev_init(&hank_dev, &init_fops);
hank_dev.owner = THIS_MODULE;
hank_dev.ops = &init_fops;

// cdev_add returns 0 if success
if (cdev_add(&hank_dev, MKDEV(major_num, 0), NUM_DEVICES) != 0) {
    pr_alert("[Module][%d] Failed to add char device for device: %s.\n",
                current->pid, DEVICE_NAME);
    return -1;
}
```

註銷 character device

cdev_del	刪除 character device。
unregister_chrdev_region	釋放 kernel 已配置的 major number。

```
cdev_del(&hank_dev);
// release major umber
unregister_chrdev_region(dev, NUM_DEVICES);
```

file_operations

cdev_init 初始化時先傳入通用的 file_operations。
在 open handler 被調用時，根據 inode 查詢到的 minor number 判斷開啟的裝置後指派對應的 handler 處理。
init_fops 為初始化帶入的預設 handler。

```
static struct file_operations init_fops = {
   .owner = THIS_MODULE,
   .open = general_open
};

static struct file_operations hankdev_fops = {
   .owner = THIS_MODULE,
```

```
    .read = hank_read,
    .write = hank_write,
    .open = hank_open,
    .release = hank_release,
};

static struct file_operations hankdev_fops2 = {
    .owner = THIS_MODULE,
    .read = hank_read,
    .write = hank_write2,
    .open = hank_open,
    .release = hank_release,
};
```

根據 minor number 不同再在 general_open 裡將對應的 struct file_operations 指派給傳入的 struct file *參數並調用之。

```
tatic int general_open(struct inode *inode, struct file *file) {
    printk(KERN_INFO "[Module] general_open\n");

    switch (iminor(inode)) {
        case 0:
            file->f_op = &hankdev_fops;
            file->private_data = "1";
            break;
        case 1:
            file->f_op = &hankdev_fops2;
            file->private_data = "2";
            break;
        default:
            pr_err("[Module][%d] Try to open device with unsupported minor number: %d\n",
                    current->pid, iminor(inode));
            return -ENXIO;
    }

    if (file->f_op && file->f_op->open) {
        return file->f_op->open(inode, file);
    }

    return 0;
}
```

識別開啟的裝置

調用 iminor(inode) 可以得知裝置的編號，藉此識別裝置。

```
static int hank_open(struct inode *inode, struct file *file) {
    pr_info("[Module][%d] Hank device with minor %d was opened\n", current->pid, iminor(inode));
    return 0;
```

```
}
```

建立 device file node

mknod 建立 device node

mknod -m MODE /dev/<name> Type major minor
Type: c character device, b block device, p pipe

範例:

```
mknod -m 666 /dev/hank0 c 248 0
```

若為動態註冊的 device driver, 可透過下面指令抓取 major number。

```
grep devone /proc/devices | awk '{print $1;}'
```

程式建立 device node

class_create	在 /sys/class 註冊 device 類別
device_create	在 /dev 建立 node, 路徑為 /dev/<DEVICE_NAME>

```
// register class to /sys/class
cls = class_create(THIS_MODULE, DEVICE_NAME);

// create device to /dev/<device_name>
// create multiple devices
for (i = 0; i < NUM_DEVICES; i++) {
    device_create(cls, NULL, MKDEV(major_num, i), NULL, "hank%d", i);
    pr_info("Devices created on /dev/hank%d\n", i);
}
```

程式移除 device node

device_destroy	移除 device node
class_destroy	移除在 /sys/class 下註冊的 device 類別

```
// destroy multiple devices
for (i = 0; i < NUM_DEVICES; i++) {
    device_destroy(cls, MKDEV(major_num, i));
    pr_info("Devices /dev/hank%d destroyed\n", i);
}
// unregister class
class_destroy(cls);
```

Read 操作

宣告一個靜態 buffer 作為裝置資料緩衝。

```
static char msg[BUF_LEN]; /* The msg the device will give when asked */
```

調用 copy_to_user() 將 msg 複製到 user pasce 的緩衝區，讓 user 得以讀取資料。

```
static ssize_t hank_read(struct file *file, char __user *buf /* buffer from user space */,
       size_t length, loff_t *offset) {
   size_t size = 0;
   int unread = 0;

   if (length < BUF_LEN) {
       size = length;
   } else {
       size = BUF_LEN;
   }

   unread = copy_to_user(buf, msg, size);
   return size - unread;
}
```

Write 操作

調用 copy_from_user() 將 user space 的資料複製到 driver 的緩衝區儲存起來。

```
static ssize_t hank_write(struct file *file, const char __user *buf /* buffer from user space */,
       size_t length, loff_t *offset) {
   int unwrite = 0;
   // clear device buffer
   memset(msg, 0x0, sizeof(msg));

   if (length > BUF_LEN) {
       length = BUF_LEN;
   }

   unwrite = copy_from_user(msg, buf, length);

   pr_info("[Module][%d] User write %s, unwrite: %d\n", current->pid, msg, unwrite);
   return length - unwrite;
}
```

User space 測試程式

調用 fopen() 開啟裝置，將裝置當作檔案來操作。fread() 從裝置讀取緩衝資料；fwrite() 將資料寫入裝置緩衝區。

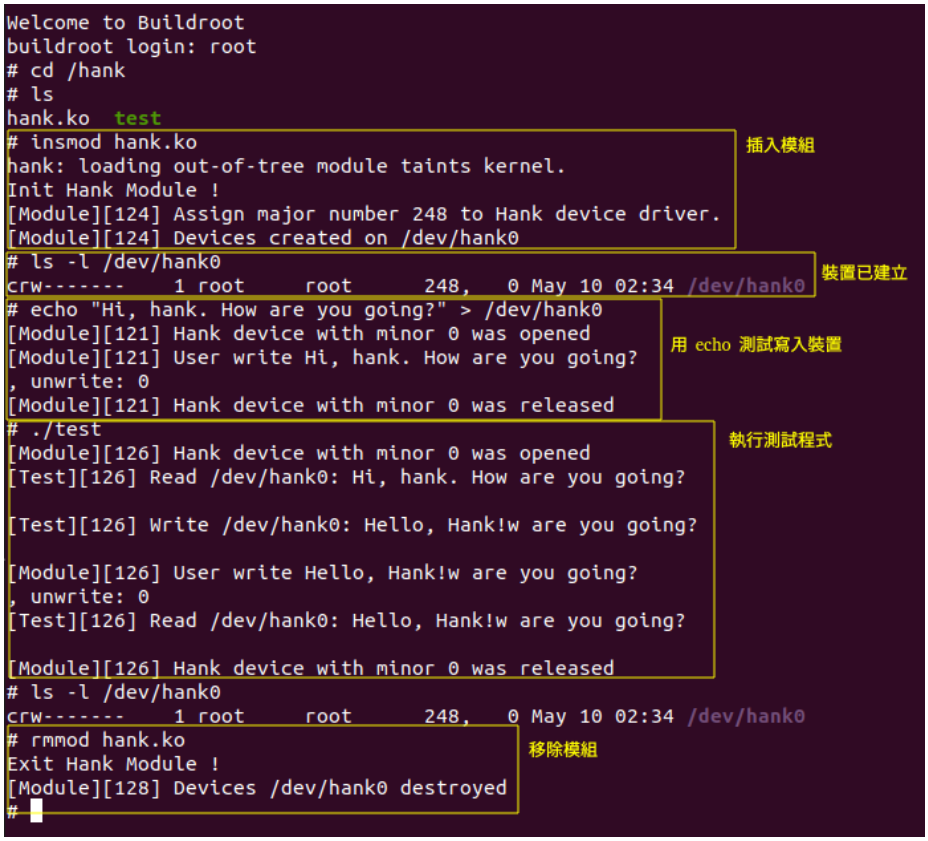
```
#include <stdio.h>
#include <string.h>
#include <unistd.h>

int main() {
   FILE *file = NULL;
   char buf[128];
```

```c
    int i = 0, sum = 0;

    file = fopen("/dev/hank0", "w+");

    if (file == NULL) {
        printf("[Test][%d] Failed to open /dev/hank0\n", getpid());
        return -1;
    }

    fread(buf, sizeof(buf), 1, file);
    printf("[Test][%d] Read /dev/hank0: %s\n", getpid(), buf);

    strncpy(buf, "Hello, Hank!\n", 12);
    printf("[Test][%d] Write /dev/hank0: %s\n", getpid(), buf);
    fwrite(buf, sizeof(buf), 1, file);

    fread(buf, sizeof(buf), 1, file);
    printf("[Test][%d] Read /dev/hank0: %s\n", getpid(), buf);

    fclose(file);

    return 0;
}
```

編譯 user space 測試程式

```
arm-buildroot-linux-uclibcgnueabihf-gcc -o test test.c
```

測試結果



Github link

https://github.com/limuheng/linux_kernel