Raspberry Pi Thermal Study

Introduction

This thermal study is centered on a credit card sized, Linux computer known as the Raspberry Pi (R-Pi), model B. Eben Upton, a design engineer for Broadcom combined an A11 core IP with peripherals, such as 2D graphics processor with a RAM module usually found in cellphones along with other bits and pieces to make a 32 bit "home computer" equivalent. The original purpose of the R-Pi was as a teaching tool for elementary, middle and high school students in the UK. As a low-cost platform (its only $35 US), there is little to impede teaching programming to everyday UK students much like a similar program based on the BBC 8 bit processors sold in the 1980's. To say the public reception of the R-Pi was good is a massive understatement. Since its release in February 2012, it has sold over 200,000 copies world-wide. The original website was completely shut down by the online order volume and sales were moved to two commercial venders. Since then the little computer has been used in dozens of ways totally beyond the original design scope.

Hardware Internals

The central component is a SOC (System on a Chip) based on a proprietary Broadcom part. It has an ARM A11 microprocessor IP embedded inside along with peripheral IO, HDMI (1080P MEG4 decoder for video), stereo audio output, some GPIO (General Purpose Input\Output) pins, an LCD panel interface and a touch screen controller. See the black rectangle just below the yellow socket in the above picture.

System RAM is 256MB in a Samsung chip usually found in cellphones that is actually the top slice of a "sandwich" package with the SOC. The SOC is completely covered by the RAM chip.

The role of hard drive for storage and operating system source is a SD flash drive. Suggested sizes are at least 2GB with an upper limit size of 8GB. SD flash used in the tests described here was a SanDisk 8GB SDHC Ultra with 30MB/sec transfer rate.

Ethernet and USB are handled by a fairly special sub-controller networking chip made by SMSC (now a part of MicroChip), a LAN9512i. This part supports the MAC and PHY for a single Ethernet port and an upstream USB 2.2 controller hub and a 2 port downstream USB controller. The parts found in the 2 R-Pi samples obtained were industrial temperature range (-40 to 85°C), no idea whether that is standard or happenstance. The chip is nestled between the two shiny metal connector bodies above.

Three regulators are on-board on top and underneath for 5 VDC, 3.3VDC and 1.8VDC. A Schottky power diode is used to protect against reverse polarity. The 5 VDC regulator is a buck-pass regulator with the

voltage drop across the Schottky diode leaving 4.7 VDC to be passed to the 3.3 VDC regulator (switching) and 1.8 VDC LDO analog regulator. The unit is powered using a standard cellphone charger through a cellphone industry standard (power only) mini-USB connector found on most recent model smartphones. Current required to operate the R-Pi device is 700 mA.

Thermal Boundaries

The SOC and RAM are specified to work from 0°C up to 50°C (32°F -122°F). The networking chip is specified to operate a full Industrial range of -40°C to 85°C (-40°F to 185°F). Usually Industrial range parts are tested "picks" from the standard manufactured output. Lately Industrial parts, especially of complicated functions, can be chosen based on an algorithm using the position the individual die has on the large wafer. The standard quality parts however might be still able to operate outside the range advertised. Over-clockers of Intel and AMD CPUs often rely on parts being specified conservatively, it's often the same way with other parts as well.

The test described here is to determine the possible limits of operating an unmodified Raspberry Pi computer on the high temperature side of its possible operating range. Hardware specifications of the entire system released to date don't indicate what upper temperature limits exist for the devices on the circuit board. In addition, stacking two chips, the SOC with the Samsung RAM creates an unknown thermal micro-environment that has to be measured as a single component. Thermal specifications of the Raspberry Pi were derived by looking at the individual components' specification sheets.

Potential Known Issue

A number of users have reported that the networking/USB port integrated circuit, a LAN9512, operates at an extremely elevated temperature. Some have reported that the elevated chip temperature is due to the Ethernet phase-lock loop power supply on the LAN9512 is connected to the 1.8VDC bus or plane and potentially in a regulation "battle" with the 1.8VDC LDO (Low Drop-Out) regulator that powers the SOC. Two analog regulators, whose outputs are connected together without a load resistance, will cause the voltage to oscillate.

On the two Raspberry Pi units available here, no direct electrical connection exists between the 1.8 VDC bus powering the SOC and the 1.8 VDC operating the Ethernet port. Voltage on the SOC 1.8VDC bus is 1.849 and the Ethernet-PLL 1.8 VDC supply is operating at 1.776 VDC. These measured voltages are referenced to test-point TP2 (Ground). Later we'll see other differences as well.

What can be reported is that this particular integrated circuit, the LAN9512, is fairly unique. It supports a single Ethernet port with both the MAC and PHY internal to the chip. It also supports 2 downstream USB ports and one upstream USB port. This combination of functions with the specific choice of peripherals (keyboard, mouse) might be part of the reason for the extra heat experienced by other users.

Test Configuration

All of the cable connections required to operate the R-Pi have been extended outside of the test chamber. Only the Raspberry Pi was exposed to the thermal conditions of the test. Partial reasoning is to avoid damaging more equipment than the DUT but mostly to prevent loading the test chamber with un-needed thermal mass. Reduced thermal mass allows faster temperature changes to occur in the test area around the DUT.

Data acquisition equipment used was a 10bit 8 channel Analog to Digital convertor module made by DATAQ, a DI-149. This module is powered via the USB connector on a small nano-ITX form factor AMD Geode computer (IBOX-500) running Windows XP Embedded. There is some irony in using a Windows operating system on a small computer to log data from a much smaller Linux computer. The small AMD Geode computer is operating only 200 MegaHertz slower than the clock speed of the Raspberry Pi (700 MHz) and at twice the required power!

The data logging software installed on the Geode was the shareware version of DATAQ's WinDAQ software. Sample collection rate was dialed way back to 10 samples per channel per second. Thermal events are not so speedy as to require a fast sampling rate.

The actual temperature sensors used were Analog Devices TMP-36 in the TO92 "plastic transistor" form. These were chosen because of their low cost, the R-Pi devices were open with no intruding heat sinks and they matched in signal level the DAQ module, (0 to 5 VDC). Each sensor was glued to the chip with cyanoacrylate (superglue) since there were no means otherwise of attachment that would not come loose when the part got hot. Although thermocouples might have been more responsive to temperature changes, the ease of use of the Analog Devices unit was deemed suitable considering the equipment being tested and the access to the specific data acquisition equipment at hand.

As expected, the plastic used in the TO-92 cases of the TMP-36 devices slowed thermal transits to approximately 10 seconds on most devices. The thermal resistance of the superglue although measureable did not significantly impede the test. The plastic used to encapsulate the R-Pi's three major integrated circuits was evidently denser than the plastic of the TO92 sensors and able to pass heat faster, on the order of 2 to 3 seconds. A preliminary examination with a thermocouple showed the differences in thermal behavior of the circuits versus the temperature sensors.

Devices attached to the Raspberry Pi included: A USB keyboard and trackball used to allow operation of the test-enclosed R-Pi; a large format HDMI equipped computer monitor; and the Geode computer used to run the logging software was also the USB cable power source for the Raspberry Pi.

All of the temperature sensors except one were physically attached to the chip covers with superglue. There was no electrical contact made with the Raspberry Pi circuitry. Previous manual measurements of current draw matched the value advertised by the vendor, 700 mA. Since all power to the device was through the 5VDC input, total power was 3.5 Watts. Voltages were extremely difficult to measure during the test, however at various times manual measurements during the first 24 hours verified the regulators were staying within specifications, although hot.

The one temperature sensor not attached was an ambient air temperature sensor. It was located to one side of the circuit board and separated from the DUT by one inch (2.54 cm).

The test chamber was a custom built, heat insulated enclosure using incandescent light bulbs as a heat source (four 75 Watt lamps). A standard incandescent bulb emits 98% of the power used by the bulb as infrared radiation. Even those lamps designated as "heat lamps" do not improve on that statistic. The remaining 2 percent is visible light. A baffle was inserted between the Raspberry Pi DUT (Device Under Test) and the lights preventing directly radiated infrared from heating the DUT. All connections for sensors and the DUT were brought through a closed port and used extensions when necessary.

Temperature control for the test chamber was through a simple analog control system switching power on and off to the heat lamps. Simple architecture, easy to install with the only downside being shortened bulb life. The temperature control using its own ambient air sensor was able to operate within a +/- 1/2 degree C window successfully, more accurate than the testing sensors that were rated at +/- 1 to 2 degrees C.

First Look at the Raspberry Pi

When operating the Raspberry Pi in home or office, the three major integrated circuits, the SOC/RAM chip, the networking interface chip and the first regulator RG2 (5VDC) all get noticeably warmer than ambient temperature. Measurements show that the SOC/RAM unit gets an additional 20° C hotter than ambient at normal office ambient of 24°C. The Networking chip and RG2 follow suit with 19° C hotter. When starting at 24°C (75°F) as an ambient temperature, the chips stay within their specified operating temperature range. Evidently the test device exhibits at least a portion of what has been reported on web sites affiliated with the Raspberry Pi as one that has the 1.8 voltage bus error. The network interface chip *is* operating hotter than what would be considered normal. Although it appears the R-Pi device will operate in this fashion perhaps indefinitely, it's likely to be a long term issue.

When the air temperature around the Raspberry Pi is raised to 50°C (122°F) in the test chamber, the three chips continue their 20/18 offset from ambient temperature.

Software function used to exercise the DUT was admittedly light on the hardware exercise. Basically the Midori web browser built into the Raspbian operating system image was used to display video on the

ubuntu.com\tour website. This computer when used as a computer programming teaching aid will be slightly less taxed. (Text editing will likely task the system less than rendering photographs on web pages.)

Future tests hopefully can use a full suite of Linux-based hardware exercise software, there hasn't been any yet written for the Raspberry Pi. The relatively new design with the grouping of semi-unique features will require a specially programmed software package to properly evaluate the specific thermal behaviors.

Although there is a documented programming model for the Raspberry Pi, a number of specific hardware details remain hidden by Broadcom. The programmable chip design used as the foundation of the Raspberry Pi architecture is deemed proprietary and a full disclosure evidently will not happen. Comprehensive hardware data sheets for the Broadcom SOC are not publicly available.

When the system was pushed up to 55°C (131°F), the web browser stalled and the system went comatose. Temperature of the SOC/RAM was 75°C (167°F). (Since the SOC is under the RAM no direct temperature measurements of the SOC can be made.) The network part was running at 73°C (163° F). When the system was shut down and rebooted, it would not operate until the temperature of the SOC/RAM parts dropped to 50°C. This failure mode is not unique to the Raspberry Pi. Systems running Linux and Windows as well as other operating systems do exactly the same. Although not a listed public feature of the hardware, a thermal shutdown or at least a clock throttle might be in play. At that point, First Look was finished when the system successfully rebooted **after** it had been cooled.

Test Scenario One

Operating the Raspberry Pi at 50°C or 122°F indefinitely looks to be possible. This computer though is no different than other computers; the longer it's operated at high temperature, the shorter the useable long-term life will be. The system was run for 48 hours at 50°C with no failures.

Disconnecting a USB Microsoft keyboard and a Logitech track-ball dropped the operating temperature of the LAN9512 chip by 5°C.

An early aborted test run had an unusual test result. A fault in some of the test circuitry caused 3 of the sensors to short and overheat. The shorted sensors caused the super glue to melt causing the failed sensor parts to separate from the tested circuits. The computer continued to run for another 5 to 6 minutes even when temperatures at those spots presumably exceeded each of the packaged circuits' upper limits. Power was shut off and another run was initiated after the faulty temperature sensors were replaced. No damage appears to have been done to the Raspberry Pi.

The R-Pi was successfully run for a full 48 hour period at 50°C (122° F). Operation in a long timeline data collection has borne out the earlier observation of an 18 to 20 degree C "thermal offset" above local ambient temperature. This temperature offset is the circuitry self-heating as it operates. It remained fairly consistent with different software operations initiated manually on the Raspberry Pi. This offset basically is additive to whatever the ambient temperature is.

Suggested Remediation

It might be possible to enable some cooling techniques to allow the system to operate above 50°C but if it requires more than a heat sink, the effects of diminishing returns kicks in. A number of users reporting hot network chips (LAN9512i) have installed stick-on RAM chip heat sinks to enable some cooling. This would be especially effective if the R-Pi is operated without an enclosure.

If it is found that the 1.8VDC regulators are in a regulation "battle", a new board revision for the Raspberry Pi will be needed to eliminate the issue. **In the meantime installing the R-Pi in a tight enclosure or into some larger enclosed system will count against the possibilities of relieving the heat on the system and is not recommended.**

A reasonable expectation would be that enclosure of the R-Pi circuit board in a tight fitting plastic enclosure will likely increase the local (inside the enclosure) ambient temperature of the circuit components. These temperatures might be beyond the design specifications of the individual devices. Especially if the outer ambient temperature (external to the enclosure) is close to the upper limits found in this test. A number of similar enclosures have been designed by enthusiasts of the Raspberry Pi. This test doesn't look at any of those enclosures. All tests were done on a board operated without any enclosure.

With whatever remedial method is used to deal with the thermal issue of the LAN9512 chip, for the education and hobby markets (both overlapping the other), Raspberry Pi is nearly ideal, an inexpensive system operated in a comfortable environment that can be mass produced in ten thousand unit lots. Those interested in constantly on, long-term use for current Raspberry PI units might want to invest in a couple of heat sinks and forego the plastic or wood enclosure.

For commercial or professional systems, there are other x86 and ARM based systems capable of running at higher temperature, maybe not as cheap, or as small, but they do exist.

Future Tests

The Raspberry Pi will be "tested" formally and informally for quite some time by interested students world-wide. One discussion followed was the idea of putting the Raspberry Pi on a balloon payload and use it to control a number of experiments. That prompted interest in performing these tests and tests not performed yet, especially those tests down at low temperatures like those found at 100,000 feet (62Km) altitude. If the device can operate in near-space, it might be suitable for real space.

As a teaching device, it is ideal. System images currently customized for the Raspberry Pi hardware all come with the usual abilities of downloading more free software. This makes the $35 price a valuable investment with incredible returns. A number of magazines and web sites have popped up supporting the R-Pi.

Using cellphone parts in a device meant to operate as a desktop programming environment is genius. The parts are cheap; they have been tested by the millions in the field. The parts are commodities in the sense that possibilities exist for replacement devices even if the original companies disappear. Now that

Raspberry Pi has been released, it seems likely someone might try their hand at something similar with its own unique features.

A final observation: the Raspberry Pi components, specifically the SOC and the RAM module as noted, were originally designed for use in cellphones. Typical operation of cellphones in the 1980's would emphasize intermittent behavior since most users at that time were using their cellphones sporadically. The current crop of smart phones have fairly replaced most traditional laptop functionality and are operated more and for much longer periods of time. The pose of this user generation is with our heads bowed looking down to the phone in our palms. With the Raspberry Pi, perhaps the attention of younger members of society will return at least part of the day to the desktop.

Study was performed by Miles Wade, Systems Engineer, Scalar USA as a public service.

Data released under GPL version 1.