Mobile Embedded Systems: Research & Education

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Outline

• A New Course on Smartphones at UCSB
• Recent Research on Embedded Computer Vision at UCSB
A New Course on Smartphones at UCSB

• Course modules:
  1. HW platform
  2. OS and SW development platform
  3. Applications
  4. Low-power design technologies

• Received donation of 15 Droid phones from Google

• Homeworks and class projects involved several compute-intensive applications on energy-constrained smartphone platform
Module 1: Hardware Components

- Powerful mobile processors
  - Trend: multi-processors within a single SOC
- Dedicated chips for display driver, touchscreen control, GPS, bluetooth, WiFi more…
- Display/touchscreen
- Storage/Memory
- Communications/Connectivity
- Graphics
- Various sensors
  - Accelerometer, proximity, light, temperature, etc.
- Camera(s)
- Battery
Which is more expensive
– Smartphones or Netbooks?
Estimated BoM: US$178.96
## Apple iPhone 3G S Major Components and Cost Drivers

### US Dollars

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Multi-Source Probability</th>
<th>Component Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toshiba</td>
<td>High</td>
<td>Flash Memory NAND, 16GB, MLC</td>
<td>$24.00</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Display Module 3.5” Diagonal, 16M Color TFT, 320 x 480 Pixels</td>
<td>$19.25</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>Touch Screen Assembly Capacitive, Glass</td>
<td>$16.00</td>
</tr>
<tr>
<td>Samsung</td>
<td>Low</td>
<td>Application Processor ARM Core, Package-on-Package</td>
<td>$14.46</td>
</tr>
<tr>
<td>Infineon</td>
<td>Low</td>
<td>Baseband HSDPA/wCDMA/EDGE, Dual ARM926 and ARM7Core</td>
<td>$13.00</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>Camera Module 3 Megapixel Auto-Focus</td>
<td>$9.55</td>
</tr>
<tr>
<td>Samsung (with Elpida die)</td>
<td>High</td>
<td>SDRAM - Mobile DDR 2Gb Package-on-Package (Mounted on Application Processor,</td>
<td>$8.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bluetooth/FM/WLAN Single Chip, WLAN IEEE802.11b/g, Bluetooth V2.1/EDR, with FM and RDS/RBDS Receiver</td>
<td>$5.95</td>
</tr>
<tr>
<td>Broadcom</td>
<td>Low</td>
<td>Memory MCP 128Mb NOR Flash and 512Mb Mobile DDR</td>
<td>$3.65</td>
</tr>
<tr>
<td>Infineon</td>
<td>Low</td>
<td>RF Transceiver Quad-Band GSM/EDGE, Tri-Band WCDMA/HSDPA, 130nm RF CMOS</td>
<td>$2.80</td>
</tr>
<tr>
<td>Infineon</td>
<td>Low</td>
<td>GPS Receiver Single Chip, 0.13um, with Integrated Front-End RF, PLL, PM, Correlator Engine and Host Control Interface</td>
<td>$2.25</td>
</tr>
<tr>
<td>Infineon</td>
<td>Low</td>
<td>Power IC RF Function</td>
<td>$1.25</td>
</tr>
<tr>
<td>Murata</td>
<td>Low</td>
<td>FEM Quad-Band GSM, Tri-Band UMTS Antenna Switch and Quad-Band GSM RX RF SAW Filters</td>
<td>$1.35</td>
</tr>
<tr>
<td>Dialog</td>
<td>Low</td>
<td>Power IC Application Processor Function</td>
<td>$1.30</td>
</tr>
<tr>
<td>Cirrus Logic</td>
<td>Low</td>
<td>Audio Codec Ultra Low Power, Stereo, with Headphone</td>
<td>$1.15</td>
</tr>
</tbody>
</table>

### Rest of Bill-of-Materials

- $48.00

**Total Bill-of-Materials**: $172.46

**Manufacturing Costs**: $6.50

**Grand Total**: $178.96

*Estimated Pending Complete Analysis

[Link to full teardown report](#)
Notable Chips Inside

• ARM 11 Samsung S3C6400
  – Technology: 65nm; Pipeline depth: 13
  – Clock speed: 600MHz; L1 cache: 32KB
  – DVFS power management
  – Rich HW accelerators for multimedia (multi-format codec)
• AKM semiconductor electronic compass
  – 3-axis devices - detects device movement relative to magnetic north
  – reorient a map displayed on the screen to correspond with the direction the user is facing
• STMicro accelerometer
  – 3-axis devices - determine device orientation or inclination
The Radios Inside

- **Infineon Cellular Transceiver (< $3)**
  - Quad-band GSM/EDGE; Tri-band W-CDMA/HSDPA
  - 130-nm RF CMOS

- **Infineon PMB8878 baseband chip ($13)**

- **Infineon GPS Receiver (< $3)**
  - 130-nm RF CMOS

- **3 TriQuint PA modules**

- **BRCM single-chip Bluetooth/FM/WLAN**
  - Represents the ongoing trend of higher integration, by putting all of these functions into one chip
  - Previously, to implement these functions, 3G employed two devices: a WLAN chip and a Bluetooth IC
Inside Google’s Nexus One: Qualcomm's QSD 8250 Snapdragon Chipset

- Supports GSM, GPRS, EDGE, HSPA networks
- 1 GHz CPU; 600MHz DSP
- Integrated 3G mobile broadband
- Support for Wi-Fi® and Bluetooth® connectivity
- Built-in seventh-generation gpsOne® engine with Standalone-GPS and Assisted-GPS modes
- High-definition (720p) video decode, and multiple video codec support
- High-performance 3D graphics – up to 22M triangles/sec and 133M 3D pixels/sec
- High-resolution up to WXGA (1280x720) display support
- 12-megapixel camera support
- Multiple audio codecs:
- Support for mobile broadcast TV
- Support for Windows Mobile®, Android, and a number of Linux®-based operating systems
# Smartphone: Display/Touchscreen

<table>
<thead>
<tr>
<th>Phone Model</th>
<th>Display Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple iPhone 3GS</td>
<td>3.5” TFT (480x320)</td>
</tr>
<tr>
<td></td>
<td>Multi-touch</td>
</tr>
<tr>
<td>Nokia n900</td>
<td>3.5” TFT (800x480)</td>
</tr>
<tr>
<td></td>
<td>Single-touch</td>
</tr>
<tr>
<td>RIM BlackBerry “Tour” 9630</td>
<td>2.4” TFT (480x360)</td>
</tr>
<tr>
<td></td>
<td>No-touch</td>
</tr>
<tr>
<td>Samsung “Instinct” s30</td>
<td>3.1” TFT (240x432)</td>
</tr>
<tr>
<td></td>
<td>Single-touch</td>
</tr>
<tr>
<td>T-Mobile G1</td>
<td>3.2” TFT (320x480)</td>
</tr>
<tr>
<td></td>
<td>Multi-touch</td>
</tr>
</tbody>
</table>
Module 1: Hardware Components

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  - Trend: multi-processors within a single SOC
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- Graphics
- Various sensors
  - Accelerometer, proximity, light, temperature, etc.
- Camera(s)
- Battery
Module 2: Mobile OS and SW Development Platform

• Apple iPhone OS
• Android for Googlephones
• WebOS for Palm Pre
• Maemo OS for Nokia phones
• Blackberry RIM OS
• Windows CE (market share dropped from 23% in 2004 to 9% in 2009)
• ......
Android OS

• Software platform based on Linux 2.6
• Developed by Google and Open Handset Alliance
  – Since November 2007, 47 members
  – Open source code, under an Apache License
• Emulators on Mac, Windows, and Linux
Supported Devices

- Supported architectures
  - ARM, MIPS, x86, Power Architecture
- Available mobile phones
  - HTC G1
  - HTC Hero
  - Motorola Droid
  - Nexus One
  - More are coming
Android Anatomy
It’s an App World!

225,000+ iPhone apps (as of June 2010) and 110,000+ Android apps (as of Aug. 2010)

Source: AndroLib http://www.androlib.com/appstats.aspx
Module 3: Applications

- Accelerometer-based Applications
- Mobile TV
- Context/Location Awareness
- Mobile Health
- Mobile Social Network
- Handheld Games
- Embedded Computer Vision
- Mobile Search
- ....
Class Projects

• Bump-like applications (http://bu.mp/) – “a quick way to connect two phones by bumping them together. Exchange phone number, photos, or compare friends with just a bump.”
• Communication bridge – using smartphone to bridge two devices which do not use the same communication protocols; Tethering.
• BlueHeart: Health monitoring
• Mapping CV algorithms/codes to mobile GPU
  – CUDA for desktop GPU; OpenGL ES for mobile GPU
• ....
BlueHeart: Health Monitoring Using Tricorder

- Tricorder: a mobile health sensor device detecting
  1. ECG (electrocardiograph),
  2. SpO₂ (saturation of peripheral oxygen),
  3. Bioimpedance
  4. Acceleration of body carrier’s movement.

- BlueHeart: An Android application displaying and utilize the data collected by the Tricorder.
Hardware
Hardware setup
BlueHeart Application
Education: Research Experience for HS Students

- Two high school students selected during summer 2010
  - Project 1: Medical image viewer on mobile platform
  - Project 2: 3D visualization and user interface on smartphone platform
Completed Viewing/Zoom-In/Zoom-out Functions in 4 Weeks

434 pixels

181 pixels

91x217

360x868
Completed Primitive 3D Rotation Function in 4 Weeks

1st page, Java

2nd page, C code

rotation

More rotation

A bit more rotation

Even more rotation
Recent Research on Embedded Computer Vision at UCSB

- Mobile Image Search with Multimodal Queries
  - CVPR2010 Workshop on Mobile Vision

- GPU-Accelerated Face Annotation for Smartphones
  - ACM MM2010, Technique demonstration
  - ECCV 2010 Workshop on Computer Vision on GPU
Mobile Image Search with Multimodal Queries

- Image search based on
  - Text/voice
  - Visual
  - Location

* CVPR2010 Workshop on Mobile Vision
GPU-Accelerated Face Annotation for Smartphones

1. take a picture or select from gallery
2. detect face regions
3. recognize faces, tag with names
4. upload photos
5. link to address book
6. update database

Ref: ACM MM2010, Technique Demonstration
ECCV 2010 Workshop on Computer Vision on GPU
System profiling

<table>
<thead>
<tr>
<th>Task</th>
<th>Time (sec)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face detection</td>
<td>1.5</td>
<td>17.6</td>
</tr>
<tr>
<td>Landmark detection</td>
<td>0.7</td>
<td>8.2</td>
</tr>
<tr>
<td>Feature extraction: Gabor wavelet</td>
<td>5.1</td>
<td>60.0</td>
</tr>
<tr>
<td>Feature extraction: LDA</td>
<td>1.0</td>
<td>11.8</td>
</tr>
<tr>
<td>Feature classification</td>
<td>0.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Total</td>
<td>8.5</td>
<td>100</td>
</tr>
</tbody>
</table>

- Platform: Nvidia Tegra (dual-core ARM Cortex-A9 @1GHz)
- Image size: 640x1000
- Training images in database: 15
- Face region is aligned and scaled to 64x80 before feature extraction
CPU-GPU co-design

CPU
- OpenCV face detection
- face landmark detection
- similarity comparison

GPU
- Gabor face feature extraction
- convolving face image with 40 different Gabor kernels
GPU Acceleration

- Face detection
- Landmark detection
- Gabor face feature extraction
- Similarity comparison

CPU only

CPU + GPU
## Wide Range of GPU Core Choices

<table>
<thead>
<tr>
<th>GPU model</th>
<th>workstation</th>
<th>desktop</th>
<th>netbook</th>
<th>smartphone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nvidia Tesla (C1060)</td>
<td>240</td>
<td>128</td>
<td>16</td>
<td>*</td>
</tr>
<tr>
<td>Nvidia GeForce (G92)</td>
<td>602</td>
<td>675</td>
<td>450</td>
<td>110</td>
</tr>
<tr>
<td>Nvidia ION (GeForce 9400M)</td>
<td>141.7</td>
<td>70.4</td>
<td>12.8</td>
<td>4.2</td>
</tr>
<tr>
<td>PowerVR SOC (SGX530)</td>
<td>933.12</td>
<td>705</td>
<td>54</td>
<td>*</td>
</tr>
<tr>
<td>OpenGL</td>
<td>CUDA, DirectX, OpenGL</td>
<td>CUDA, DirectX, OpenGL</td>
<td>CUDA, DirectX, OpenGL</td>
<td>OpenGL ES</td>
</tr>
<tr>
<td>API</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: spec not available
Reference: wikipedia, Nvidia website, Imagination Technology website
Research focus: mobile GPGPU?

• Can a mobile GPU be a powerful accelerator, similar to its role in the desktop/server platforms?
• Characterize ultra-low-power GPU for energy/performance tradeoffs
Experimental setup

- Targeting 3 mobile platforms

<table>
<thead>
<tr>
<th>SOC</th>
<th>CPU</th>
<th>GPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tegra dev board*</td>
<td>Nvidia Tegra</td>
<td>Nvidia</td>
</tr>
<tr>
<td></td>
<td>dual-core ARM Cortex-A9 (1GHz)</td>
<td></td>
</tr>
<tr>
<td>Google Nexus One Smartphone</td>
<td>Qualcomm Snapdragon</td>
<td>ATI/AMD</td>
</tr>
<tr>
<td></td>
<td>dual-core ARM Cortex-A8 (1GHz)</td>
<td></td>
</tr>
<tr>
<td>Motorola Droid Smartphone</td>
<td>TI OMAP 3430</td>
<td>PowerVR</td>
</tr>
<tr>
<td></td>
<td>dual-core ARM Cortex-A8 (600 MHz)</td>
<td>SGX530</td>
</tr>
</tbody>
</table>

- Driving applications:
  - Image analysis and feature extraction
  - Racian denoising

- Development environment:
  - Android OS;
  - Java (application) + C/C++ (core computation)
  - GPU API: OpenGL ES 2.0 (No CUDA support at this time)

*Note: Tegra dev board has expansion board connectors*
Preliminary Performance/Power/Energy Measurement

- Platform: Nvidia Tegra

<table>
<thead>
<tr>
<th></th>
<th>CPU</th>
<th>GPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (sec)</td>
<td>3.1</td>
<td>1</td>
</tr>
<tr>
<td>Power (W)</td>
<td>3.7</td>
<td>4.0</td>
</tr>
<tr>
<td>Energy</td>
<td>11.5</td>
<td>4</td>
</tr>
</tbody>
</table>
Comparison of mobile & desktop GPU/CPU

<table>
<thead>
<tr>
<th>Model</th>
<th>Language</th>
<th>Performance</th>
<th>Consumed Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desktop CPU</td>
<td>Intel i7 @2.8 GHz</td>
<td>C</td>
<td>21 fps</td>
</tr>
<tr>
<td>Desktop GPU</td>
<td>Nvidia GTX 285</td>
<td>CUDA</td>
<td>180 fps</td>
</tr>
<tr>
<td>Mobile CPU</td>
<td>ARM Cortex-A8 @1 GHz</td>
<td>Java</td>
<td>0.185 fps</td>
</tr>
<tr>
<td>Mobile GPU</td>
<td>ATI</td>
<td>OpenGL ES</td>
<td>1.24 fps</td>
</tr>
</tbody>
</table>

Test image for desktop: 181*217 @20 iterations
Test image for mobile: 256*256 @20 iterations

*: Estimated from the measurement results in the paper “Power Efficient Large Matrices Multiplication by Load Scheduling on Multicore and GPU platform with CUDA”

**: Measured results. Running on Google Nexus One
Summary

• The worldwide smartphone market grew by 50 percent last year and the trend will likely continue in the next few years
• The explosive growth of smartphone apps will continue
  – Strong demands for more compute-power without consuming more energy
• Multimedia content analysis is required for many new apps but real-time performance still challenging under current HW platform
• Smartphone is an excellent and exciting component for CE curriculum and research