Module NXT

Please sit close to the screen: there will be lots of small code shown...
Presentation Overview

Overview  Non-technical overview of LEGO®MINDSTORMS®NXT from a community and user standpoint

HW and SW  Description of NXT hardware and software from a developer perspective

Examples  (1) Using TinyOS as a firmware, (2) an intelligent algorithm

Q & A  There will be time for discussion and future research ideas

Lab  Drawing for the NXT 2.0 and lab exercise using it

Note 1: LEGO has sponsored a NXT 2.0 kit
Note 2: LEGO®, MINDSTORMS® are trademarks of LEGO®. The tutorial contains pictures from Atmel ARM7 documentation, and from LEGO documentation.
Note 3: There is additional material included: Many slides are supplementary and included for future reference.
Module NXT

ESWEEK 2009
http://nxtgcc.sf.net

Rasmus Ulslev Pedersen
rup.inf@cbs.dk
Outline

1. Aim of Tutorial
2. Introduction
3. Open Source
4. Sensors
5. Inside NXT C 101
6. Firmware Programming
7. ARM7
8. NXT Software
9. Debugging NXT
Aim

• How the open source universe around Lego Mindstorms NXT is structured
• Talk about a world that stretches from high-schools to adults and from building bricks to programming in assembler
• Emphasis on the overview and the programming aspects
• Participants will be able to see where in the NXT programming spectrum their interest match most
• Use the tutorial to get started with open source programming on NXT
Introduction

- Description of open source hardware and software
- LEGO business models are discussed
- The old RCX
- NXT in several (online) communities
- Overview of how NXT can be programmed in different environments
Some Mindstorms History

• 10 years since Mindstorms was released
• First LEGO Mindstorms was the LEGO RCX: Successful
• LEGO intended it to be a closed source product, but...
• It was soon hacked:-)
• The open source strategy was pursued even more with the present LEGO Mindstorms
• A Goldplated NXT and a limited edition Black NXT was produced in relation to the 10 year anniversary
NXT Development

- Development of NXT started in the 2004
- Initial group was Ralph, Steven, John, and David
- First prototypes were circulated on a limited number basis inside the current MUP group and a select few outside that group
- MUP: Jan 2006, 5 people
- MUP II: Nov. 2005, 11 people
- MDP: 2006
- MCP 2: 31 persons, 100 chosen from 10000 applicants
- MCP 3: 2008-2009
- MCP 4: Next slide
LEGO Design Routines

- Lego has a group of people who has the privilege of talking directly to LEGO staff
- Under non-disclosure agreements (NDA)
- First group of MCPs (MUP) were a select group
- Used as a sounding board for the ideas that went into developing the first LEGO MINDSTORMS NXT.
- MCP 4 is commencing as we speak
Lego Education

- Lego has a website for educational activities
- Strong focus on university segment
- LEGO MINDSTORMS NXT comes in educational sets
- Rechargeable battery and extra building pieces
- Sold with site licences that accompany the NXT
- Different sales curve from retail (slow start, longer product life)
Mindstorms Community

- Mindstorms community is large and diverse
- Blogs, forums, large events, books, the MCP program and more
- NXTStep and the NXTasy blogs
- Lugnet is a large LEGO fanclub
Schools

- Many schools participate in First LEGO League
- A tournament where current theme is played out
- The idea is to have adults lead or mentor a team of children aged 9-14 (16 outside the US)
- NXT is used to complete a challenge put out by the FLL management
Business Models

- LEGO earns money on NXT by selling the kit itself
- Licences to educational institutions are also revenue source
- First version of LEGO MINDSTORMS NXT was released in the beginning of 2007
- A second version appeared in the fall of 2009 (biannual release schedule:-)?
- NXT 2.0 is shipped with a different set of standard sensors (color sensor)
- Spring releases at toys fairs which is then ready for Christmas sale
LEGO SYSTEMS

- LEGO partly produce and package NXT on their factory in Billund
- Staff around NXT development is not big
- Firmware development team is in control of the software development
- National Instruments (NI) designs the NXT-G environment
- The careful selection of close partners makes for long-time stability
Firmware Releases

- NXT is a complex product compared to other LEGO products
- Requires focus on quality
- Updated versions released on the official MINDSTORMS website (http://mindstorms.lego.com)
- First firmware had the version number 1.1 (or 1.0...) and the current released version for NXT 2.0 is versioned 1.28
Partners

- Many institutions, companies, groups, and individuals have a stake in NXT
- National Instruments is presumably the most important
- MIT, Tuft, Carnegie Mellon, and others are also active
- Others such as nxtprograms
- Number of large events
- This includes Brickfest
- There has also been a MINDSTORMS NXT Sumo Competition
NXT Alternatives

- NXT is not completely alone...
- Sun Spots from Sun/Oracle
- Fisher-Technic offers a new robot controller which is based on an ARM9 processor running at 200MHz
- Various evaluation kits: mbed, IAR, etc.
- However, it is difficult to match dealer network, community, and history of LEGO
Source and Documents by LEGO

NXT Firmware Open Source  Complete software for the NXT firmware, which can be compiled with a compliant C compiler.

Software Developer Kit  A kit with software for controlling NXT remotely from a host computer. It includes a description of the NXT virtual machine.

Hardware Developer Kit  Description of the possible sensor and actuator interfaces for NXT. This is extensively used by third-party sensor vendors.

Bluetooth Developer Kit  It includes the communication protocol for controlling NXT over a Bluetooth connection.

Demo  Show PDF files which are important for firmware replacements...
Schematics

• Lego published the schematics
• Can see which pins of the ARM7 MCU is connected to what ports
• Lego uses Orcad for its schematics, which is a commercial program
Analog/Digital Protocols

- NXT features both analogue and digital interfaces to its sensors.
- Sensors are based on an analogue to digital conversion.
- Signals are fed into the ARM processor for further processing.
- Digital sensors are made with an I2C compliant protocol.
- I2C is a two wire protocol that allows for a number of devices on the shared bus.
- It can be monitored with a logical probe.
NXT-G Blocks

- LEGO provides a proprietary programming language for LEGO MINDSTORMS NXT called NXT-G
- G implies it is a graphical programming language
- Places NXT-G programming blocks in a sequence that involves the usual programming constructs such as loops, branches and computations
- Tutorials and small videos with instructions for a given task
- Show Robocup NXT-G program in NXT-G...
Firmware Source

- LEGO MINDSTORMS NXT comes with an open source operating system
- Operating system is written in ANSI C
- Source code fundamentally access the physical layer such as input and output ports of the ARM processor
- Another part provides an abstraction layer to these services (Show the HPL, HAL files...)
- Operating system is a traditional round robin scheduler
- Services each a number of modules
Modules Overview

- Each module is centered on a logical or a physical unit in NXT
- Example: the display or the user interface
- The virtual machine a logical module
- Each time the virtual machine is serviced it can/will execute a number of bytecodes
- A 1 ms period (system tick) services all modules
- Show scheduler...
Fantom PC/Mac Interface

- LEGO has released an interface both for the PC and the Macintosh
- Linux is not supported at this point
- Firmware image in NXT is updated via a USB cable connection
- NXT is programmed from NXT-G either over USB or Bluetooth
- We will revisit this Fantom DLL when GNU debugger is discussed
Sensor Partners and Independent Manufacturers

- A limited number of third-party sensors exists
- Hitechnic, Mindsensors, and Vernier
- Hitecnic produces its sensors in a standard LEGO sensor housing
- Mindsensors make its sensors available in different shapes and forms
- Vernier specializes in natural sciences experiments
- DCP
Standard Sensors

- Input and output ports feature a 6-wire RJ12 connector
- Ultrasonic distance measurement sensor, a light intensity sensor, a sound sensor, a touch sensor, and motors

Standard Lego Mindstorms NXT sensors and a NXT-G block
Mindsensors

- Camera
- Realtime Clock
- Acceleration (2, 3, and 5 axis reading)
- Dual Infra Red Obstacle Detector
- Motor Multiplexer for NXT
- Magnetic compass
- Pneumatic Pressure Sensor
- High Precision Infrared distance sensor (short, medium, long range)
- Various accessories: port splitter, cables, plugs, sensor kit, tools
Selected NXT sensors from Mindsensors

(g) Multi-axis acc.  (h) Magnetic compass

(i) Pneumatic pressure  (j) Infrared distance

(k) Sensor building kit  (l) Temperature
Hitechnic

- Prototype Board
- Gyro
- IR seeker
- Compass
- Color sensor
- Acceleration/tilt
- Sensor and motor multiplexer
- Accessories: Cables
Sensors from Hitechnic

(m) Color
(n) Gyro
(o) Multiplexer
(p) Prototyping board

If you don’t think "How fast can I get these sensors...", then something is wrong:-)"
Custom Sensors

- It is possible to create custom sensors
- EAGLE is a CAD program for creating specialized PCBs
- The PCBs can be fabricated at places such as Olimex.
- Olimex accepts EAGLE files (probably easier than Gerber files)
- Sensors can be prototyped for under $50
EAGLE

It is easy to modify a schematic in EAGLE
Create a (non-functional...) Demo Temperature Sensor

- Select components
- Take some pin header
- Search for termistor and add it
- Wire it
- Try
  File->Run->bom.ulp
Create a Temperature Sensor

- Try
  
  File->Run->bom.ulp
Create a Temperature Sensor

- Create the board
- File->Switch to board
Create a Temperature Sensor

- Take Tools->Auto...
- Check the layers (View->Display/hide layers)
- Perhaps a little overdoing with not using a single layer board...
- Resize the board by using MOVE corners
Create a Temperature Sensor

- Make Gerber files
- Run `excellon.cam` from the File->CAM
- Use GerbView (or similar to inspect files)
- or Textpad...
NXT C Programming 101

Just to refresh out C programming skills
  • NXT types
  • Function pointers
  • void pointers

```
typedef struct
{
  ULONG ModuleID;
  UBYTE ModuleName[FILENAME_LENGTH + 1];
  void (*cInit)(void* pHeader);
  void (*cCtrl)(void);
  void (*cExit)(void);
  void *pIOMap;
  void *pVars;
  UWORD IOMapSize;
  UWORD VarsSize;
  UWORD ModuleSize;
} __attribute__((__packed__)) HEADER; /*nxtgcc converter*/
```
NXT C Programming 101

- Pointers *
- Address of &
- Dereferencing *

```
ULONG* pUL;
ULONG someUL;
someUL = 4;
pUL = &someUL;
*pUL = 5;
//Now someUL == 5
```
NXT C Types

- typedef
- struct
- enum
- #define

```c
typedef struct
{
    ULONG someUL;
    ...
} SOMESTRUCTYPE;
...
enum
{
    SOMEENUMVAL0,
    SOMEENUMVAL1, SOMEENUMVALEND = SOMEENUMVAL1,
};
...
ifndef SOME_H_FILE
define SOME_H_FILE
// code
endif //SOME_H_FILE
```
Embedded Programming

- A central micro processor controls NXT
- A second small micro processor assisting it
- Code is compiled to machine instructions which are executed one at a time
- NXT allows for firmware updates, which is the basis for alternative operating systems
**NXT Firmware**

- NXT actually consists of two different firmwares.
- The main firmware controls the interaction with the user, and radio communication to other NXTs.
- An ATmega48 generates the pulse width modulation (PWM) signals for the three motors.
- It also provides input regarding the state of the push buttons on the NXT.
- Host side SDK which allows for interaction with the NXT via a DLL.
NXT Inside

- (a) ARM7 MCU
- (b) ATmega48 MCU
- (c) CSR BlueCore4 Bluetooth radio
- (d) SPI bus and touchpad signals
- (e) high-speed UART behind input port 4
- (f) output (generally motor) port
- (g) USB port, (h) four-button touchpad
- (i) 100x64 LCD display
ARM to AT48 Communication

- AVR to ARM: Buttons, ADC values, and Battery
- ARM to AVR: Motor control etc.
- Show `m_sched.h` file...

```c
typedef struct
{
    UWORD       AdValue[NOS_OF_AVR_INPUTS];
    UWORD       Buttons;
    UWORD       Battery;
} IOFROMAVR;

typedef struct
{
    UBYTE       Power;
    UBYTE       PwmFreq;
    SBYTE       PwmValue[NOS_OF_AVR_OUTPUTS];
    UBYTE       OutputMode;
    UBYTE       InputPower;
} IOTOAVR;
```
Firmware Enhancements

- Firmware enhancements are possible only because Lego released the software as open source
- IAR is a commercial compiler used by LEGO
- It was recently released in a free version for Mindstorms
- The other option for programming the existing firmware is to use GCC
Firmware Replacements

- A growing number of firmware replacements available
- Examples: lejos, NQC, pbLua, and RobotC
- A different example is TinyOS
- leJOS is based on a small virtual Java machine. It is a firmware replacement that allows for Java programming on Lego Mindstorms NXT. There is extensive support in forms of tutorials, well-developed APIs, and Netbeans/Eclipse programming IDEs at the leJOS website.
- Lua is a scripting language (see Lua website). It is said to perform faster than other scripting languages. Ralph Hempel has ported Lua to Lego Mindstorms NXT and labeled it pbLua
- Not eXactly C (NXC) is language similar to C. It is supported on Lego Mindstorms NXT by John C. Hansen and available from http://bricxcc.sourceforge.net/nbc/. It is built on top of the Next Byte Codes (NBC) compiler. It is a firmware replacement.
The free IAR compiler can be downloaded from IAR’s homepage

It is an industry strength programming environment called *Embedded Workbench*

It interacts with a JTAG programmer connected to Lego Mindstorms NXT via the IAR C-SPY debugger

The visualSTATE program interacts with the C-SPY debugger to give a graphical view of the debugging session
The GCC compiler can be downloaded from the nxtgcc home page.

It is an *arm-elf-gcc* compiler.

There exists several good toolchains such as WinArm, CodeSurgery etc.

Show nxtgcc Eclipse project...

- `binsert.c`
- `nxtgcc.rfw`
- `ConvertNxtGcc.java` and `NGU.java`
- `Source-xx` → `Source copy`
- `m_sched.map`
GCC Compliance Process

- Changes needed to make the source code compile with an arm-elf based GCC
- See details in `ConvertNxtGcc.java` program
- First versions of NXTGCC were error-prone
- IAR supports, and Lego uses, nested flexible array members
- GCC does not support this
- Key was to change the nested flexible array to become a fixed size nested array
Nested Array

Show Display.txt in SourceOrig and in Source

```c
typedef struct {
    UBYTE FormatMsb;
    ...
    UBYTE PixelsY;
    /*nxtgcc converter*/
    UBYTE Data[1];
}__attribute__((_packed__))
BMPMAP;
```
• Characterized by a number of modes, exception types, and interrupts
• Associated with each mode is a current program status register (CPSR)
• Each exception and interrupt type is associated with a priority
• 6 privileged modes named system, svc, abort, fast interrupt, interrupt, and undefined mode
• They can all modify the CPSR
• The unprivileged user mode cannot modify the CPSR
The Bible: Atmel doc6175.pdf

The ARM7 processor used in NXT is underlined.
Periodical Interval Timer
The PIT timer generates the system tick.
Memory Controller

The MC generates the abort exception
MCU Overview I
SAM-BA, SPI, TWI, AIC, SSC, etc.
MCU Overview II

SAM-BA, SPI, TWI, AIC, SSC, etc.
ARM MCU Features

JTAG, Thumb, ARM

7. Processor and Architecture

7.1 ARM7 TDMI Processor
- RISC processor based on ARMv4T Von Neumann architecture
  - Runs at up to 55 MHz, providing 0.9 MIPS/MHz
- Two instruction sets
  - ARM® high-performance 32-bit instruction set
  - Thumb® high code density 16-bit instruction set
- Three-stage pipeline architecture
  - Instruction Fetch (F)
  - Instruction Decode (D)
  - Execute (E)

7.2 Debug and Test Features
- Integrated EmbeddedICE™ (embedded in-circuit emulator)
  - Two watchpoint units
  - Test access port accessible through a JTAG protocol
  - Debug communication channel
- Debug Unit
  - Two-pin UART
  - Debug communication channel interrupt handling
  - Chip ID Register
- IEEE1149.1 JTAG Boundary-scan on all digital pins
ARM MCU Peripherals and Memory Mappings

The Big (Small...) Picture
ARM MCU Peripherals and Memory Mappings

Main memory
Main memory remapping
ARM MCU Peripherals and Memory Mappings

Peripherals such as timers
ARM MCU Peripherals and Memory Mappings
System Peripherals such as interrupt controller
ARM7 Registers

- The CPSR defines the characteristics of the current mode
- It can mask (ie. not allow) interrupts and fast interrupts
- The CPSR includes a flag whether the ARM7 is executing thumb code or arm code
- There is a register file which includes 37 registers
- Each register is 32 bit wide
- Each mode uses 17 registers
- Registers R0-R12 are shared between `usr`, `sys`, `svc`, `abt`, `irq`, and `und` modes
- The `fiq` mode has its own banked version of the R8-R12 registers
- All modes have their own stack pointer and link/return pointer: R13 and R14
- The program counter, \( pc \), is placed in R15
ARM and Thumb Instruction Sets

- The ARM instruction set is 32 bit
- Thumb instruction set is 16 bit
- Most of the code in NXT is compiled toward the Thumb instruction set
- Thumb code is more dense than ARM
- Exception and interrupt handlers are compiled to ARM code

Demo ARM compilation.

NXT schematics
## ARM Pins

Show PDF with ARM...

<table>
<thead>
<tr>
<th>PCB</th>
<th>Port/pin</th>
<th>ARM7 pin</th>
<th>ARM7 PIO</th>
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<td>DIGIA0</td>
<td>1/5</td>
<td>15</td>
<td>PA23/PGMD11</td>
</tr>
<tr>
<td>DIGIA1</td>
<td>1/6</td>
<td>10</td>
<td>PA18/PGMD6/AD1</td>
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<tr>
<td>DIGIB0</td>
<td>2/5</td>
<td>38</td>
<td>PA28</td>
</tr>
<tr>
<td>DIGIB1</td>
<td>2/6</td>
<td>13</td>
<td>PA19/PGMD7/AD2</td>
</tr>
<tr>
<td>DIGIC0</td>
<td>3/5</td>
<td>41</td>
<td>PA29</td>
</tr>
<tr>
<td>DIGIC1</td>
<td>3/6</td>
<td>16</td>
<td>PA20/PGMD8/AD3</td>
</tr>
<tr>
<td>DIGID0</td>
<td>4/5</td>
<td>42</td>
<td>PA30</td>
</tr>
<tr>
<td>DIGID1</td>
<td>4/6</td>
<td>6</td>
<td>AD7</td>
</tr>
</tbody>
</table>

- Port 1 through 4 are mapped to general purpose input output pins
- Most ARM7 pins are multiplexed
- Pin 6 on inout port 1-3 both can serve as GPIO pins and as an analog to digital converter (ADC)
- The *Lowspeed* module use the GPIO pins to *bit-bang* an I2C protocol
Memory Layout and Dynamics

- Flash memory is initially mapped to address 0x0000 0000
- Flash is also accessible at address 0x0010 0000
- NXT immediately branches to the reset handler that is defined in CStartup.S
- It uses a temporary stack in the RAM area
- The reset handler sets up the stacks for the interrupt handler (IRQ), the undefined instruction handler (UND) stack, and the user stack (USR)
- The USR stack is used when the normal code executes
- IRQ stack is obviously used when the IRQ handler is invoked: it branches to the correct interrupt service routine (ISR)
- Controlled by writing the address of that ISR into the advanced interrupt controller (AIC) source vector register (SVR)
- Example: each of the three timers (TC0, TC1, TC2) have an ID, and that ID is used as index in the AIC SVR vector

Next: Memory Layout
Outline

Aim of Tutorial

Introduction

Open Source

Sensors

Inside NXT C 101

Firmware

Programming

ARM7

NXT Software

Debugging NXT

Memory Layout

[Diagram of memory layout]

Notes about the NXTGCC memory layout figure:
- Not drawn to scale
- Strikethrough: not used in standard firmware
- Interrupt and exceptions is handled in assembler
- Some details omitted for clarity
Memory Layout

- The stacks on NXT (i.e. ARM7) are fully descending stacks
- Using the instructions STMFD and LDMFD
- Postfix FD depicts that we are working with a full descending stack

TODO: Show code with descending stacks
Undefined Instruction Stack Setup

- Undefined stack setup in Cstartup.S
- The illegal memory access (ABT) stack is set up before the undefined instruction stack

/* Set up Undefined Instruction Mode and set UND Mode Stack*/

.EQU UND_STACK_TOP, (ABT_STACK_TOP - ABT_STACK_SIZE)
msr CPSR_c, #ARM_MODE_UND | I_BIT | F_BIT
mov sp, r0 /* Init stack UND */
sub r0, r0, #UND_STACK_SIZE
Post Boot

- Remapping of address 0x0000 0000 such that it is now the RAM and not the flash that is accessible from address 0x0000 0000
- Main reason for this is that we need to service interrupts even when the NXT flash-based file system is being written to
- Remapping the memory ensures that the interrupt vector table is access in RAM
- All interrupt service routines are linked into the .fastrun segment

Show segments in file.
NXT Running

- Mostly taking place in the Thumb compiled code
- Interrupt is asserted from one of the ARM7 peripheral sources then that interrupt service routine takes over
- Most peripherals in NXT are associated with a software module
Modules

- Each module is built from an header file, a C file, and .iom file
- Layered in a hardware physical layer (HPL), and a hardware abstraction layer (HAL)
- HAL files start with the letter c followed by an underscore, while the HPL files start with the letter d
- Show a module...
## NXT Software Modules and ARM7 HW Peripherals

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<th>ARM Peripherals</th>
<th>Note</th>
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<td>Main control</td>
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<td>AVR via I2C/TWI</td>
<td>4 buttons</td>
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<td>Input</td>
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<td>Loader</td>
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<td>Lowspeed</td>
<td>GPIO, PWM</td>
<td>I2C emulation</td>
</tr>
<tr>
<td>Output</td>
<td>AVR via I2C</td>
<td>Motor control</td>
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<tr>
<td>Sound</td>
<td>SSC</td>
<td>Loadspeaker control</td>
</tr>
<tr>
<td>UI</td>
<td>-</td>
<td>Menu system</td>
</tr>
<tr>
<td>Timer</td>
<td>PIT</td>
<td>Operating system tick</td>
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<tr>
<td>Bluetooth</td>
<td>SPI, GPIO</td>
<td>Communication control</td>
</tr>
<tr>
<td>Communication</td>
<td>UDP, UART, SPI</td>
<td>USB, RS485, and BT</td>
</tr>
</tbody>
</table>

### Abbreviations:
- I2C: Inter-integrated circuit
- TWI: Two-wire interface
- PWM: Pulse width modulation
- AIC: Advanced interrupt controller
- MC: Memory controller
- SSC: Synchronous serial controller
- PIT: Periodic interval timer
- SPI: Serial peripheral interface
- UDP: USB device port
- UART: Universal asynchronous receiver transceiver
NXT Modules

Scheduler This is the main scheduler: m_sched. It works in a round robin fashion with a 1 ms system *tick*. It will call each of the modules listed below using function pointers. There is an initialization phase in which each module’s cInit method is called. Then the system starts calling the cCtrl methods. Termination is done via calls to CExit.

Button It handles the four buttons on top of NXT. Principle: It uses the AD converter peripheral Button 0 is read as? Button 1-3 is read as an AD converted value.

CMD This is the Lego virtual machine. It reads the executable files stored in flash and creates a RAM space for runtime information. The rxe file contains bytecode instructions, bytecode scheduling, and run-time data.

Comm It takes care of the BT, USB and the Highspeed port. Peripherals used: SPI to BT, USB, and USART in RS485 mode.
NXT Modules

Display
It is code for accessing the pixels of the 100 x 64 pixel display. It is possible to both set pixels, write characters, and strings (it is a matter of abstraction). There is a font included with the NXT. There are eight text lines on the display. It accesses the serial peripheral interface (SPI) hardware peripheral. The SPI works by writing data to a slave (the display in this case) over the master out slave in (MOSI) line. It receives data from the slave over the master in slave out line (MISO). The data flow is synchronous and is regulated by a serial clock (SPCK) line. The display receives a command from the ARM7 specifying which line is to be written, and then it receives the actual data for that line.

Input
The input sensors are plugged into the 4 input ports on NXT. NXT will know which type of sensor is plugged into a port. It can be a temperature sensor, sound, lows speed, and so on. The lows speed sensor is an I2C/TWI compliant sensor.
NXT Modules

IOCtr1 | This module controls the booting and power down sequences of NXT. It will write to the AVR what the power should be and what the PWM for the motors should be. The IOCtrl module uses the I2C(TWI) hardware peripheral to relay this information to the AVR. It also uses the advanced interrupt controller (AIC), by having it call an I2C handler routine.

Loader | File management is achieved by the loader module. It reads, writes, creates, and deletes files in the NXT flash. It resides in the upper part of the flash memory starting from the value of the memory address STARTOFSERUSERFLASH in d_loader.h. It uses the memory controller (MC) peripheral module of the ARM7. No read while writing: the methods that perform erase and write of flash pages are placed in RAM. This is achieved by marking the methods with __ramfunc, which tags the method to belong to a section called .fastrun. The .fastrun section are placed in the DATA=RAM area.
NXT Modules

Lowspeed
An I2C compliant device can be connected to one of the four input ports. The lowspeed module handles the communication and recognizes the connected sensor as either the standard ultrasonic device, or a custom device. It uses an IRQ handler that is invoked via the AIC hardware peripheral: It utilizes the pulse width modulation controller (PWM) peripheral to generate the clock.

Output
Motors are connected to NXT through the three output ports: A, B, and C. The module communicates the motor output to the AVR via the I2C bridge. It is managed by struct, which is passed to the AVR from the ARM7 that controls this communication line. The information that controls the motors are an output mode and a PWM frequency for each motor. Thus, the output module make use of the hardware peripherals TC0, TC1, TC2, to monitor motor C, A, and B respectively. Interrupt handlers: the tacho count bookkeeping.
NXT Modules

Sound
A loudspeaker with 8 bit resolution is controlled by the sound module. It plays sounds which are files residing in the NXT file system. Each time cCtrl method of the sound module is called, then it either plays a sound, continues to play a sound, or closes the sound file that has been played. The module utilizes the synchronous serial controller (SSC) hardware peripheral. With the SCC providing the AC signal (SOUND_ARMA from PA17) to the SPY0030A audio driver, NXT can play sounds. It uses the peripheral DMA controller (PDC) to handle the transmission of the bitstream to the speaker.

UI
The module manages the menu system, selected files, icons, animations, etc. on NXT. It responds when an user press on of the buttons on NXT.

Timer
NXT is programmed around a system tick of 1 ms. This property is supported by the timer module that use the periodic interval timer (PIT) hardware peripheral to maintain a 1 ms counter.
Debugging Overview

- Easiest way to debug NXT is to use the light sensor
- We can find the memory location that controls the GPIO pin
- Other choices is to use a JTAG debugger
Light Sensor Port

```c
//Turn on an input port
#define ON(port)
{
    *AT91C PIOA SODR = PORT_TO_PIN(port);
}
```

Turn on a light sensor on an input port for low-level debugging...
Show section 15.4.4 Output Control in ARM PDF...

Light sensor schematics: Show how to turn on the light sensor in code
Display Debugging

Example (from c_cmd.c):

```c
// LCD DEBUG START
int cnt = 0; // a static counter
UBYTE DebugString[50];
sprintf(DebugString,"Debug info: \%d", cnt);
if (cnt==1)
{
    cDebugString(&DebugString[0]);
}
} // LCD DEBUG END
```

Showing a debug string in the display
GDB Debugging

- We may think (initially) that we have stopped the processor
- A break point can be inserted into the code using the GCC inline assemble syntax

```c
/*
 * Trigger a breakpoint exception.
 */
__ramfunc void bsp_breakpoint(void) {
    //asm volatile (".word 0xE7FFDEFE");
    NXTGCCBREAK;
}
```
GDB

- GDB is the debugging system that is connected to GCC
- GDB system offers a remote debugging system
- USB driver to use is the Fantom SDK
- Fantom C++ files, there is a section with `extern C`"
- Read and write methods for arbitrary bytes
- Allows for an implementation of the GDB remote debugging protocol
- Debugger is arm-elf-gdb
GDB Remote Protocol

- It includes a one-byte checksum
- Comes after the # in the packet
- Problem is that the Fantom DLL does not like if we try to read from the USB if there is not something to read
- We read two characters (checksum)
- NXTGCC Fantom GDB wrapper (discussed later) writes and especially reads one character at a time to/from NXT, even though the USB endpoints are in bulk mode

Show GDB files here...
Hardware Debugging

- It is possible to create one using a 1.27 mm pitch row
- Each of the eight pins from J17 can be connected to a standard 20 port JTAG like this:
  1 → 9, 2 → 7, 3 → 13, 4 → 15, 5 → 5, 6 → 4, 7 → not connected, and 8 → 1.
- Use Segger, IAR or some open source project like OPENOCD

Using a JLink to flash an ARM7 Eval. board, while warming up for NXT to arrive in the summer of 2006.
Compiler Performance

- Eclipse is one possibility as an programming environment
- Output from compiling the firmware has been shown
- Size and memory addresses of the different sections are displayed after a successful build

Reading the compilation statistics in Eclipse
Comparison

Comparison of GCC and IAR Code Size

<table>
<thead>
<tr>
<th>Compiler</th>
<th>Packing structs</th>
<th>Size of .text (bytes)</th>
<th>Size of .data (bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCC</td>
<td>All</td>
<td>202052</td>
<td>54548</td>
</tr>
<tr>
<td>NXTGCC</td>
<td>Selected</td>
<td>180104</td>
<td>54144</td>
</tr>
<tr>
<td>GCC</td>
<td>None</td>
<td>162136</td>
<td>54228</td>
</tr>
<tr>
<td>IAR</td>
<td>(speed)</td>
<td>127552</td>
<td>49831</td>
</tr>
<tr>
<td>IAR</td>
<td>(size)</td>
<td>122440</td>
<td>49763</td>
</tr>
</tbody>
</table>

GCC compiler (arm-elf-gcc version 4.2.2) that NXTGCC uses, creates a larger code footprint than the IAR compiler does. For the flash we can compare the GCC compiler’s approx. 175 KB to the IAR compiler’s approx. 120 KB. Regarding RAM, the picture is approx. 53 KB compared to approx. 49 KB in favor of IAR.
Comparison of GCC and IAR Code Speed

<table>
<thead>
<tr>
<th>Compiler</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>NXTGCC (selected structs)</td>
<td>615</td>
</tr>
<tr>
<td>IAR (size optimized)</td>
<td>640</td>
</tr>
</tbody>
</table>

Benchmark code: Steven Hassenplug
Lego, Atmel, and the NXTGCC project provide comprehensive information about NXT. This includes hardware schematics, explanation of important protocols, and documentation for programming NXT:

- **Lego**: Hardware Developer Kit
- **Lego**: Software Developer Kit
- **Atmel**: AT91SAM7S256 aka ARM7 hardware description
- **NXTGCC** [http://nxtgcc.sourceforge.net](http://nxtgcc.sourceforge.net)