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# Final Report - Sudoku on AVR

ACE411-Embedded Microprocessor Systems

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## Introduction

The project's purpose is to implement a program to solve a  $9 \times 9$  sudoku grid on STK500. The interface used is a serial port (RS232), through which the development board receives commands and data (in ASCII format) and transmits data and messages. The 8 LEDs available on the board are also used, to display the progress of the solving procedure. An optimized algorithm for solving has been developed, to achieve fast solving time.

## Description of the program

### The sudoku solving algorithm

The sudoku solver baseline for the first 8 rows is a general purpose DFS algorithm (with pruning invalid cases), where profiling indicated that the biggest time cost is the routine for pruning (finding which are the valid values for a cell). And in order to minimize that cost, the calculations for pruning a cell are computed once and cached.

Lastly, after the first 8 rows are solved the last row is trivially solved.

### Controlling the LED progress bar

To update the LEDs that show the progress of solving, there were two options. The first one was updating the PORTA register every time we change the value of a cell and the second one was refreshing the LEDs with a 30Hz frequency. The former option would consume many clock cycles (because on every PORTA update, its new value is read from flash, which needs 3 clock cycles many times each second), when the latter would consume those 3 cycles only 30 times per second. The latter was preferred, using Timer/Counter1.

### USART interfacing

As the assignment states, the serial port is configured at 9600 baud, 8 data bits, 1 stop bit and no parity.

### Receiving from the serial port

When a character is sent to the serial port, the USART\_RXC interrupt is triggered. In the interrupt handler, based on the receiver character, if it is a command character, a flag is set,

else if it is a number it is stored in the memory. After receiving the line-feed character, the command is executed.

It is important to note that in the case of "play" command, the interrupt service routine does not call the solving function, but simply sets the solving flag and returns. This is done to return back as fast as possible, and then start solving with the interrupts enabled (when the ISR is called, the interrupts are disabled until it returns). In that way, while solving a break or a debug command can be received and executed (by interrupting the solving function). If the ISR called the solve function, until completing solving, the interrupts would be disabled, and any new characters from the serial port would not be read.

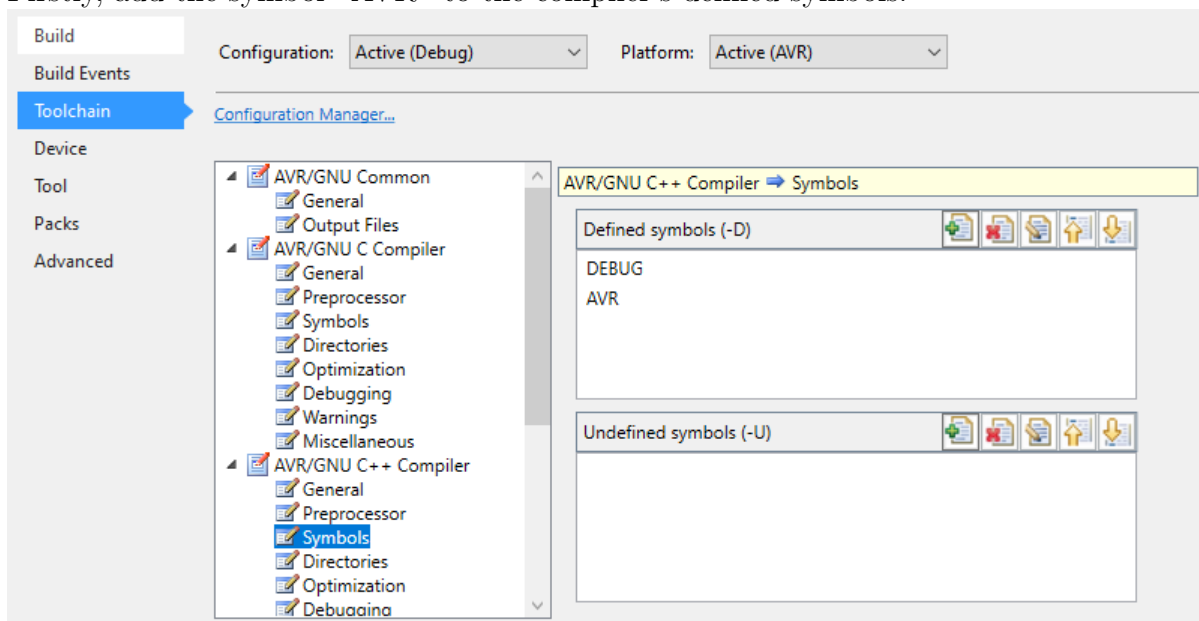
## Transmitting to the serial port

To transmit a character, a polling procedure is used. A loop is done to wait until the UDR register gets empty and then is written the character to be transmitted. In fact, in this project, polling is not affecting the system's efficiency, because the baud rate is extremely low, so the UDR register will be empty, every time we want to transmit a character (every 10000 clock cycles approximately). So, for example the "OK" sending is done inside the USART interrupt handler in the case of an "AT" command. This is not a problem, because the communication protocol described in the assignment states that the computer will wait for the reply before sending a new command.

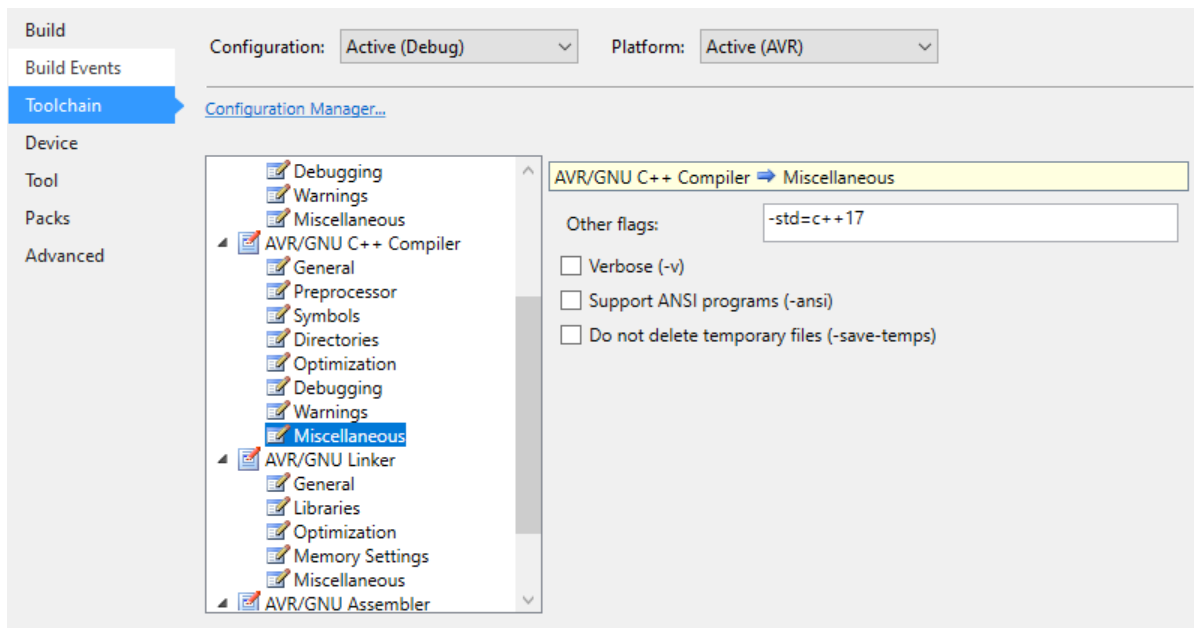
## Microchip Studio configuration - Compilation process

Since the code is written using the C++ language (using newer standards than the supported from Microchip Studio by default), some modifications should be done to the default settings of a new C++ project.

Firstly, add the symbol "AVR" to the compiler's defined symbols:



Secondly, add the flag "-std=c++17" to the compiler's flags:



The optimization level should be set to “-O2 (Optimize more)”.

Finally, the SIMULATION\_MODE should be defined (by uncommenting the line 25 of sudoku.h). When it is defined, the program will read from TCNT2 instead of UDR and will redirect its output from UDR to TCNT0. By doing that, the program can be simulated with the provided stimuli files.

The makefile should not be used with Microchip Studio, but only when using gnu-toolchain on linux system.

## Resource usage

After compiling the code, the following resource usage is reported:

```

Output
Show output from: Build
"D:\ProgramFiles\ATMEL_STUDIO_7\7.0\toolchain\avr8\avr8-gnu-toolchain\bin\avr-objcopy.exe" -O srec -R .eeprom -R .fuse -R
"D:\ProgramFiles\ATMEL_STUDIO_7\7.0\toolchain\avr8\avr8-gnu-toolchain\bin\avr-size.exe" "GccApplication5.elf"
  text  data  bss   dec   hex filename
 6822    0    88   6910   1afe GccApplication5.elf
Done executing task "RunCompilerTask".
Using "RunOutputFileVerifyTask" task from assembly "D:\ProgramFiles\ATMEL_STUDIO_7\7.0\Extensions\Application\AvrGCC.d11".
Task "RunOutputFileVerifyTask"
  Program Memory Usage : 6822 bytes 41,6 % Full
  Data Memory Usage    : 88 bytes 8,6 % Full
Warning: Memory Usage estimation may not be accurate if there are sections other than .text sections in ELF file
Done executing task "RunOutputFileVerifyTask".
Done building target "CoreBuild" in project "GccApplication5.cppproj".

```

### Program memory (flash)

Except from the code, two arrays (look up tables) are stored in flash:

- The led\_bar\_LUT (defined in sudoku.h), which contains the decoding data for the LED progress bar (holds 82 bytes).
- The div\_9\_LUT (defined in LUT.hpp), which contains pre-calculated value to make the solving process faster (holds 162 bytes).

The rest bytes ( $6822-82-162 = 6578$ ) are reserved by the code instructions.

## Static RAM (SRAM)

The global variables used to control the serial port are the struct of flags for the received character (11 bits or 2 bytes), the union for the X counters (1 byte), the union for the Y counters (1 byte) and the counter for the arguments (1 byte). The rest of the 88 bytes are used for the base\_board object (an instance of the sudoku class). Inside this object is stored the 9x9 sudoku grid as a two dimensioned array of unsigned integers.

During the solving process, the solver uses up to 790 bytes, leaving 146 bytes for context switching during interrupts.

## Simulation in Microchip Studio, using stimuli files

Three stimuli files are submitted with the code (in the folder STIMULI\_FILES):

- simple\_solve.stim, which feeds the program with one sudoku board (the one shown in the assignment), waits until the sudoku is solved and sends the results back.
- break\_debug\_test.stim, which feeds the program with the same sudoku board as above, but while solving, a “break” command stops the solving process, and using the “debug” command, the contents of some cells are read.
- two\_sudokus.stim, which feeds the program with two sudoku boards, one after another. After solving the first and sending back the results, a “clear” command is executed and then the grid is filled with the second sudoku, it is solved and the results are sent back to the serial port.

Using the Microchip Studio debugging tools (Run To Cursor and Step Into) and by watching the memory contents (e.g. the values that are completed each moment in the sudoku grid, or if the flag bits are set to true/false), the functionality of the program can be evaluated.

## Testing the code on real hardware (STK500)

### Using PuTTY

Three tests have been done on hardware using PuTTY. The content of the PuTTY terminal is provided in the following files (in the folder PUTTY\_LOGS):

- simple\_solve\_tty.log, which feeds the program with one sudoku board (the one shown in the assignment), waits until the sudoku is solved and sends the results back.
- break\_debug\_tty.log, which feeds the program with a difficult sudoku board (generated with the interface program, to slow the solving process and have the time to give manually a break command), but while solving, a “break” command stops the solving process, and using the “debug” command, the contents of some cells are read.

- `two_sudokus_tty.log`, which feeds the program with two sudoku boards, one after another. After solving the first and sending back the results, a “clear” command is executed and then the grid is filled with the second sudoku, it is solved and the results are sent back to the serial port.

On each file, an identifier is placed in the start of each line, to show who sent this command ([PC] or [STK]).

Important note: While configuring the serial connection in PuTTY, the flow control can be set either to “None”, or to “XON/XOFF” without any problem. Even when using XON/XOFF, the baud rate is so low, so the buffers of the two communicating devices (the PC and the STK) will never overflow.

### Using the interface program developed by Odysseas Stavrou – TO BE EDITED

Although the program has still some bugs (reported to Odysseas) and part of the functionality cannot be tested with it (such as the break command), it can show useful statistics for the sudoku solver. It was used to find the solving time of many sudokus. Five random sudokus of each difficulty level were solved, giving the following results:

	Game 1	Game 2	Game 3	Game 4	Game 5
Easy	31.7 $\mu$ s	43.5 $\mu$ s	151.1 $\mu$ s	52.1669 $\mu$ s	76.2 $\mu$ s
Medium	39.1 $\mu$ s	68 $\mu$ s	10.2698 ms	43.9 $\mu$ s	22.8 $\mu$ s
Hard	59.5 $\mu$ s	77.1334 ms	37.7 $\mu$ s	33.4 $\mu$ s	15.6933 ms
Ultra	23.6088 s	3.2823 s	72.0722 s	408.7206 ms	7.1807 s

In the final report (which will be submitted on the 22<sup>th</sup> of December), 100 boards of each difficulty level will be solved, to provide an accurate statistic performance analysis of the program. This procedure is postponed for now, because of the interface’s bugs.

### Performance analysis

TODO by elioudakis: Prepare this section and remove the previous one

## STK500 configuration

The STK500 development board we have received has installed the ATmega16L microcontroller, which is fully compatible with the ATmega16 used in Microchip Studio. PORTA is fully functional, and therefore connected to the LEDs. An external crystal of 10MHz is used. Since ISP (In System Programmer) programming mode is used, the following jumpers are mounted:

**VTARGET** mounted, to use the on-boards supply voltage.

**AREF** mounted, to use the AVR’s AREF as reference volatge for the A/D converter on AVR. Although the A/D converter is not used in this project, the jumper is mounted, because this is the default setting.

**RESET** mounted, to be able to use the on-board reset button.

**XTAL1** mounted, to use the external crystal.

**OSCSEL** mounted to pins 2 and 3 to use the on-board crystal signal as clock signal.

## **Fuses configuration**

TODO by elioudakis: Maybe needed if the program should be downloaded to STK from another computer.

## **Conclusion - Future work –TODO: Should change**

The requirements stated on the assignment for milestone 1 have been satisfied (interface the serial port to support all the commands and replies, implement the LED bar and store the sudoku grid in SRAM). Additionally, the algorithm to solve the sudoku is implemented, and its functionality has been tested both in simulation and on real hardware. Of course, until submitting the final report, there is the intention to optimize the code and improve the performance of the algorithm.