AVR441: Intelligent BLDC Fan Controller with Temperature Sensor and Serial Interface

8-bit AVR® Microcontrollers

Application Note

Features

- **Application Example for Controlling Brushless DC Motors**
  - **Ideal for Use as an Integrated Fan Controller**
- **Automatically Adjusts Fan Speed According to Chip Temperature**
- **Automatically Detects Fan Failures**
- **Two-Wire Interface for Remote Control and Monitoring**

1 Introduction

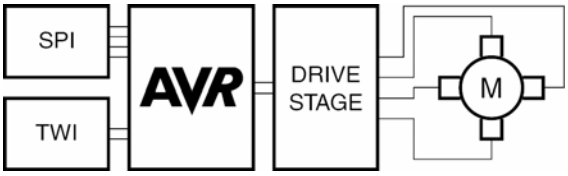
As package dimensions go down and power consumption figures goes up thermal management becomes an increasingly important factor in modern day electronics design. Perhaps the simplest form of thermal management is forced convection, i.e. increasing the dissipation of heat by moving the air inside and around the heat source. This is most conveniently done using fans, which are powered by Brushless DC (BLDC) motors. BLDC motors are commutated electronically, eliminating problems such as mechanical wear of brushes, but also reducing EMI (Electro-Magnetic Interference). The most straightforward fan designs simply spin the fan rotor at full speed, but as the number of fans tends to increase so does the noise. The noise level becomes an annoyance, which creates a demand to adjust the speed of the fan according to environmental conditions.

When cooling is not efficient components may overheat and suffer temporary or permanent failures. A modern fan must therefore be able to react to changes in temperature, mechanical wear and even physical obstacles (jamming the fan). As fans are used in computerized environments thermal control can be made more efficient if fans are connected to a master, such as the CPU in a typical PC.

This application note describes how to integrate a low-cost, feature-rich AVR microcontroller into the commutator electronics of a BLDC fan. The ATtiny25 used in this application note is a low-cost, low-power, 8-bit microcontroller based on the AVR enhanced RISC architecture. It contains 2 KB Flash program memory, 128 bytes of EEPROM memory and 128 bytes of SRAM. It has an integrated temperature sensor, an analogue comparator, a four-channel ADC and a high-speed timer/counter with PWM outputs. The Universal Serial Interface provides remote control capabilities over a Philips I^{2}C™-compatible bus.

The design is easily migrated to other low pin count tinyAVRs.

Figure 1-1. Block Schematic of Fan Controller.

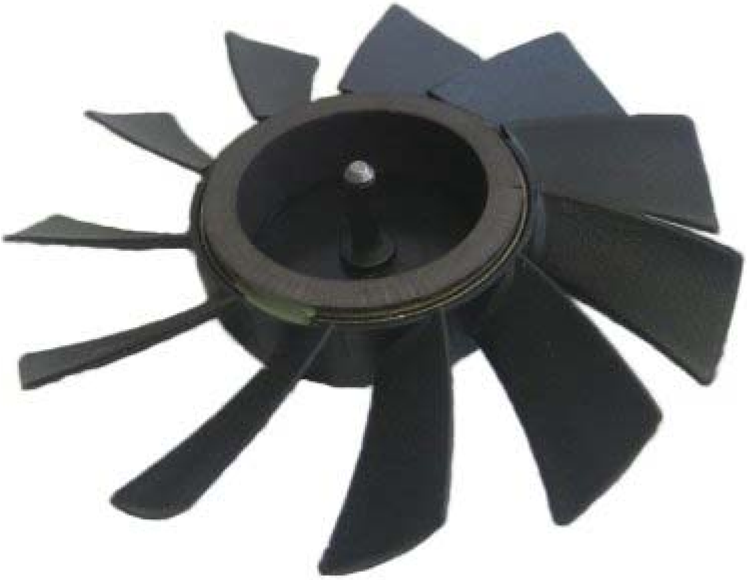


Rev. 8004A-AVR-09/05

2 Theory of Operation

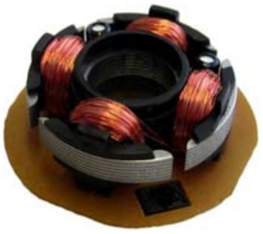
The basic brushless DC motor, commonly found in most 12-volt fans, can be broken into two main components: the rotor and the stator. As the name implies, the rotor is the part that rotates and the stator is the static construct it rotates around. The rotor houses the permanent magnets, and in the case of a fan motor, the fan blades are also attached to the rotor. See figure below.

Figure 2-1. Rotor of BLDC fan.



The motor coils are housed in the stator. In a standard two-phase BLDC motor there are typically four coils. See figure below.

Figure 2-2. Stator of BLDC fan.



As opposed to the typical electrical motor where the rotor is inside the stator, compact fans typically have the rotor on the outside of the stator.

2.1 Position Sensor

The BLDC motors typically use Hall-effect sensors for commutation information. The sensor tells the controller when to activate the coils. Hall-sensors come in two flavors: non-buffered and buffered. Non-buffered sensors have two output wires, which carry the differential voltage proportional to the currently present magnetic field. The buffered sensor has only one output, and only two possible output states: high and low. The buffered Hall-sensor requires only one wire and allows a more compact design, and is therefore the choice of sensor in this application note. It should be noted that an unbuffered Hall-sensor could readily be connected to the analogue comparator of the AVR, provided that the two input pins are available. In this design, however, the serial interface requires two pins and makes the use of an unbuffered Hall-sensor difficult (but not impossible).

A basic design for a fan controller can be very simple, provided that the only requirement is to rotate the fan; basically, two transistors controlled by a Hall-sensor will do. But in most cases there are requirements to monitor and adjust the rotating speed, either autonomously by the fan itself or by remote control via a serial interface. In addition, an intelligent fan should be able to handle situations like rotor lock, overcurrent and overheating.

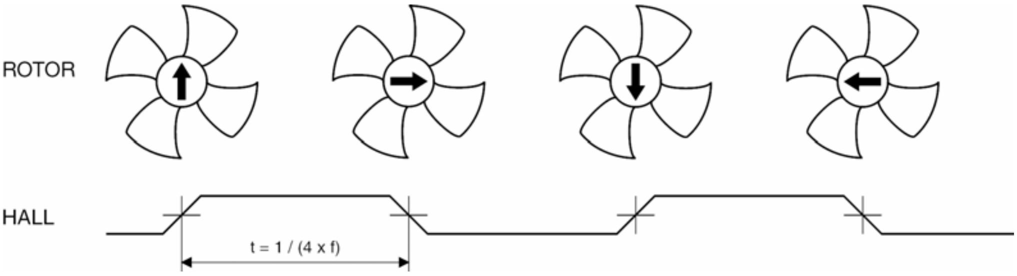
2.2 Speed Control

There are many advantages for being able to control the speed of the rotor; acoustic noise and power consumption are reduced and the expected lifetime of mechanical constructs is improved.

2.2.1 Hall Sensor Feedback

In order for the microcontroller to be able to control the rotary motion it needs to know in which phase the rotor is. For this purpose a buffered Hall sensor is used. The signal from the sensor toggles between logical high and low according to the rotational phase of the rotor, as illustrated in the figure below. The sensor signal toggles four times per revolution of the rotor.

Figure 2-3. Signal from a Buffered Hall Sensor in a Rotating Fan.



The sensor signal is used by the microcontroller to time the activation of stator coils.

2.2.2 PWM-Controlled Speed

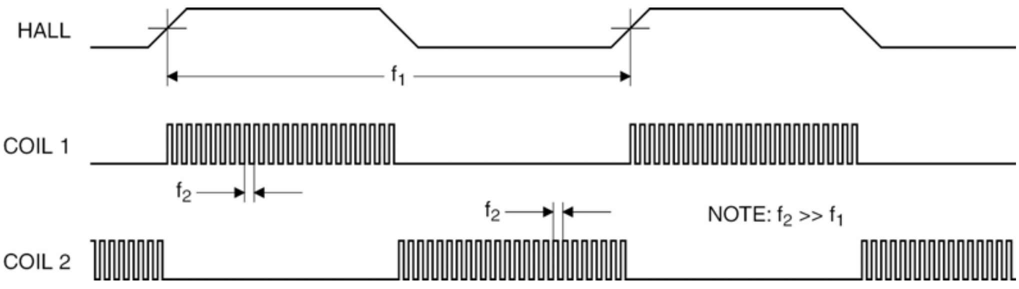
The in elaborate way to turn a rotor is to wire the sensor signal directly to a coil driving circuitry. This results in the rotor constantly trying to increase its speed of rotation until it reaches its mechanical limits. The result is a fan persistently rotating at full speed and producing the highest amount of noise.

A more elaborate method of speed control is implemented by chopping the driving signal. This means that the stator coils are still activated according to the signal from the sensor, but rather than constantly powering the coil for the entire quarter-cycle the drive signal toggles between active and inactive at a high frequency. The rotational speed of the fan is then directly proportional to the average voltage of the drive signal.

The most efficient method to obtain a chopped drive signal is to use a hardware timer/counter with Pulse-Width Modulation (PWM) outputs. The ATtiny45 is equipped with a high-speed PWM waveform generator suitable for this purpose.

The average voltage of the driving signal is directly proportional to the duty cycle of the PWM output. This means the software can easily control the speed of the fan by simply adjusting the duty cycle of the PWM outputs. The modulated coil drive signals are illustrated in Figure 2-4.

Figure 2-4. PWM-Modulated Control Signals versus Hall-Signal



2.3 Serial Interface

Many modern computer motherboards implement SMBus™ or I^{2}C to provide hardware health monitoring data, like voltages, temperature and fan speed. The SMBus interface is a 2-wire serial interface, which is very similar to and usually backward compatible with the I^{2}C™ interface.

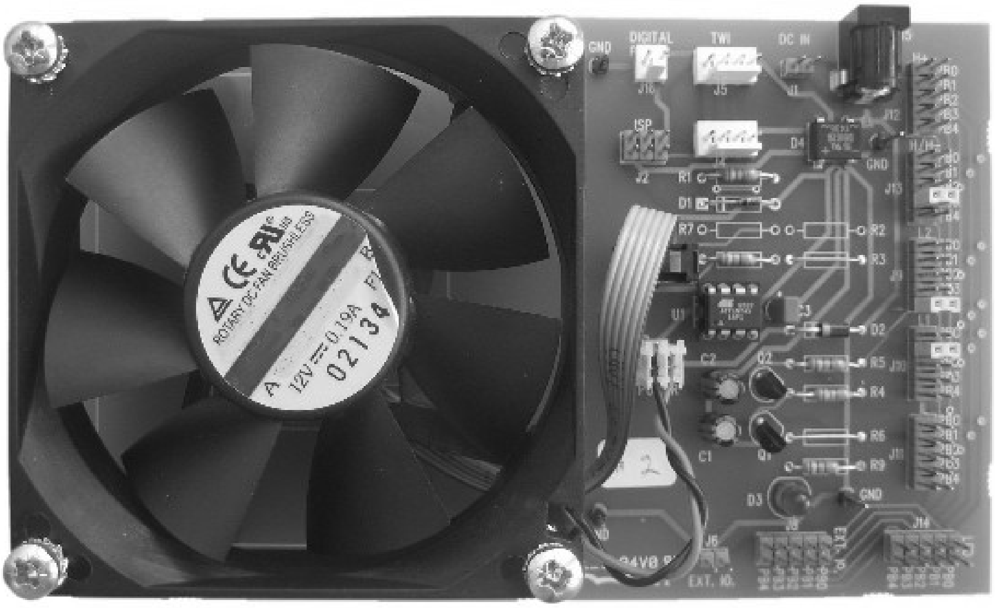
The AVR microcontroller used in this application is equipped with a Universal Serial Interface (USI), which can be programmed to operate in an I^{2}C™-compatible Two-Wire Mode. Using only two wires for communication, it is possible to remotely monitor the temperature, speed and status of the fan. In addition, the two-wire interface allows the remote device to start or stop the fan at will or to set the fan rotation to any desired speed.

3 Implementation of Fan Controller

The software implementation has been done using IAR Embedded Workbench for AVR, version 4.11A. The source codes of the fan controller are freely available.

To verify the design presented here, a printed circuit board has been created. Schematics and layouts are included at the end of this document. The fan controller is shown in the figure below.

Figure 2-5. Fan Controller, Top View.



For ease of experimentation, the design presented here has all electronic components placed outside the fan casing. In an actual implementation, most connectors and components are not required and the essential electronics are housed inside the fan.

3.1 Hardware

The hardware consists of an ATtiny45 AVR microcontroller, a Hall-effect sensor, two transistors and a few discrete components. The microcontroller is functionally and pin compatible with ATtiny25 and ATtiny85. With little or no modifications, other low pin-count AVR microcontrollers can also be used in this design.

The Hall-effect sensor has a fixed location in the fan stator. As the rotor and the permanent magnets move the magnetic flux detected by the Hall-sensor changes. The information conveyed from the Hall-sensor to the microcontroller is then used to decide which coil to activate. The coil currents can be in excess of 100 mA and the microcontroller therefore uses external transistors to control the current.

The current flowing through the activated transistor and the coil makes the coil act as a magnet, which then draws the permanent magnet in the rotor towards it and makes the rotor turn. By accurate timing of coil currents the turning of the rotor can be extended to maintain a rotary motion.

The fan controller schematics can be found in Appendix 6.1.

3.1.1 Supply Voltage Connectors

The hardware requires an external DC voltage source to operate. The supply voltage should be 12 V and the source should be able to provide some 500 mA of current. Supply voltage should be provided to one of the connectors J1 or J15.

Connectors J7 and J16 are voltage outputs, only, and intended for providing supply voltage to motor coils and the fan master. The fan master is explained later.

3.1.2 ISP and debugWIRE Interface

The fan controller has a standard six-pin ISP interface for programming purposes. Programming can be done for example through an ATAVRISP programmer, or an STK500 development board. Alternatively, with an ATJTAGICE mkII the design can be debugged in real time over debugWIRE, using only the reset pin for communication. The connector is described in the table below.

Table 2-1. Pin Layout of ISP Connector J2

Pin	Name	Description	ISP	debugWIRE
1	MISO	Serial data out	Connect	-
2	VCC	Supply voltage (1)	Connect	Connect
3	SCK	Serial clock	Connect (2)	-
4	MOSI	Serial data in	Connect	-
5	/RESET	Reset	Connect	Connect
6	GND	Ground	Connect	Connect

Notes: 1. Provided by target (fan controller)

2. Not required, when target clocked by internal oscillator

Using the ISP when the fan is connected to the system might result in random fan movements during programming. This is because the same wires that are used for ISP programming are also connected to the coil-drive transistors. Normally this is not a problem. It can, however, be avoided by temporarily removing the jumpers that connect the control signals to the transistors, or by temporarily removing the supply voltage to the fan coils.

For more information about the ISP interface, see Application Note AVR910: In-System Programming. For more information about debugWIRE, see the User Guide of ATJTAGICE mkII and the ATtiny25 data sheet.

3.1.3 Fan Connector

The fan connector is a 6-pole pin header, which carries signals to and from the motor. Signals are described in the table below.

Table 2-2. Pin Layout of Fan Connector J3

Pin	Name	Description
1	L1	Ground side connection of first motor coil
2	H+	Positive input signal of unbuffered Hall-sensor (1)
3	L2	Ground side connection of second motor coil
4	H/H-	Buffered or positive input of unbuffered Hall-sensor
5	GND	Reset
6	VH	Supply voltage for Hall-sensor

Notes: 1. Not connected, when using buffered Hall-sensor

3.1.4 Two-Wire Serial Interface

The fan controller is equipped with two connectors for two-wire serial interfacing. Several fan controllers can be cascaded and wired to one, common fan master. The serial connector is described in the table below.

Table 2-3. Pin Layout of Serial Connectors J4 and J5

Pin	Name	Description
1	SCL	Serial clock
2	SDA	Serial data
3	N/c	Not connected
4	GND	Common ground

Pull-up resistors are located at the fan master. See microcontroller data sheets for a description of the two-wire serial interface protocol. The two-wire interface is compatible with I^{2}C™.

3.1.5 Signal Routers

The fan controller is equipped with signal routers, which makes it possible to re-route signals between the microcontroller and the auxiliary components. This is useful when trying out different combinations of features and microcontrollers.

Signal routers are 2 x 5-pole pin headers, each labelled with the signal name it directs. Jumpers are used for signal routing. For example, signal router J13 directs the buffered signal from the Hall-sensor to one of the I/O-pins of the microcontroller. The table below lists all signal routers of the design.

Table 2-4. Signal Routers

Label	Signal	Description	Default
J8	EXT. IO	External input or output	N/c [(1)]
J9	L2	Transistor control signal for motor coil L2	PB4 [(2)]
J10	L1	Transistor control signal for motor coil L1	PB1
J11	IL	Current measurement signal	N/c
J12	H+	Positive end of unbuffered Hall-signal	N/c
J13	H/H-	Buffered/unbuffered signal from Hall-sensor	PB3
J14	LED	Output signal for LED drive	N/c

Notes: 1. Not connected, i.e. no jumper

2. In this case, use jumper to connect lowest row of pins (labelled PB4)

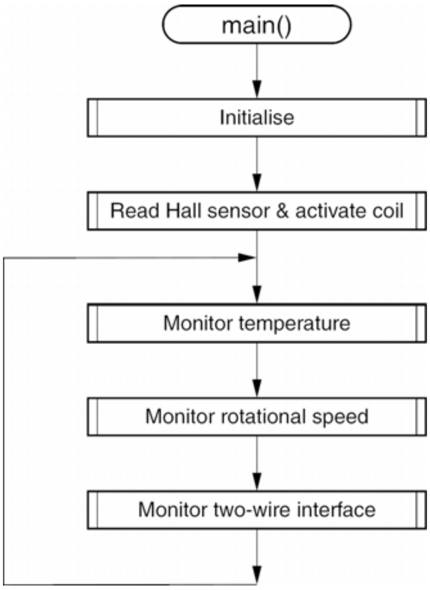
3.2 Firmware

The firmware is written entirely in C language. This is to make the design easy to understand and to make further development of the design as straightforward as possible.

3.2.1 Overview

The flow chart of the main program is shown in the figure below.

Figure 2-6. Flowchart of Main Program.

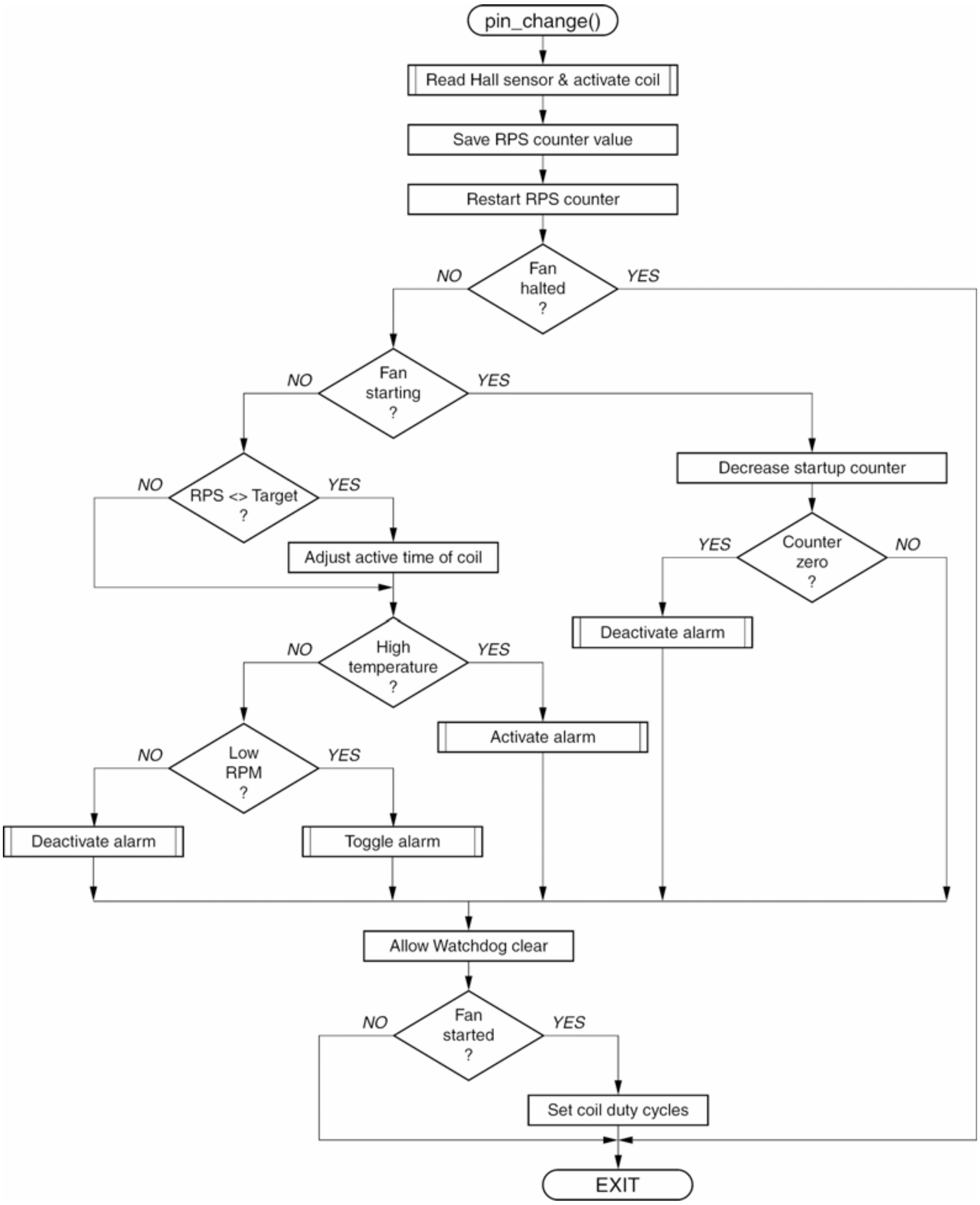


Note that the Hall sensor readings and the activation of the coils are handled by the Pin Change interrupt while the mail loop is running.

3.2.2 Interrupt Service

Every transition in the signal coming from the Hall-sensor triggers an interrupt. The interrupt service routine maintains a software extended timer/counter, monitors the state of the fan and applies fan control parameters. The flow chart of the interrupt service routine is shown in the figure below.

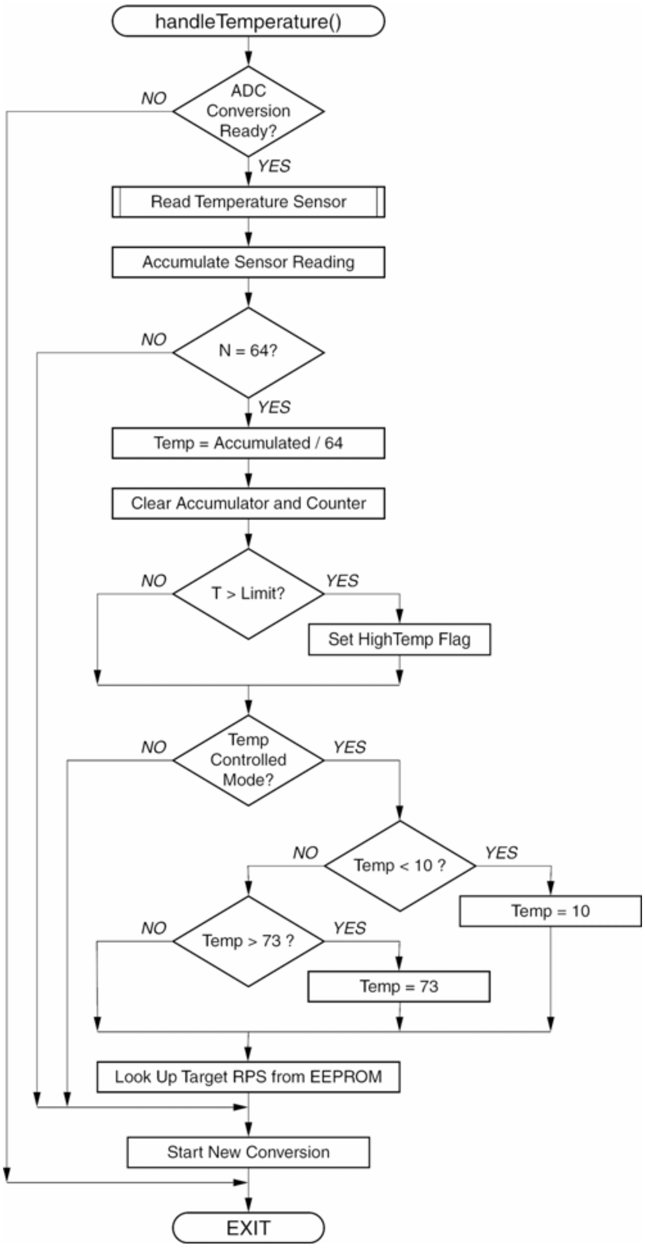
Figure 2-7. Flowchart of Pin Change Interrupt Service Routine.



3.2.3 Temperature

The firmware continuosly polls the ADC for new conversion results. When detected, the firmware reads the new conversion result from the ADC and continues to update all parameters related to temperature. The program flow is illustrated in the figure below.

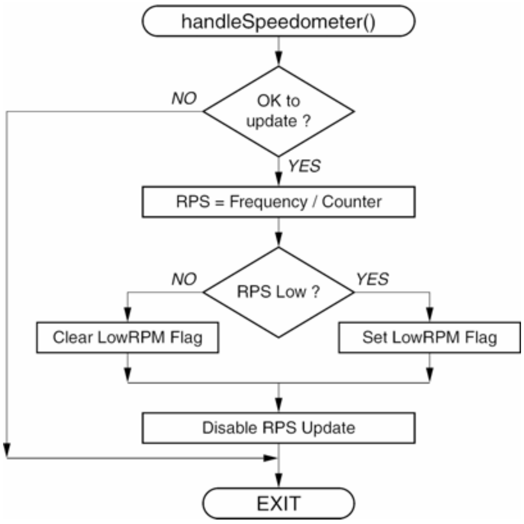
Figure 2-8. Flowchart of Temperature Monitor and Control Routine.



3.2.4 Speedometer

The rotational speed of the fan is readily evaluated as the relationsip between the frequency of the timer/counter and the actual reading of the timer/counter. Since the timer/counter is only eight bits long it has been extended by means of software (see pin change interrupt handler). In other words, the timer/counter hardware register is not used directly in this function, as seen in the figure below.

Figure 2-9. Flowchart of Rotational Speed Monitor Routine.

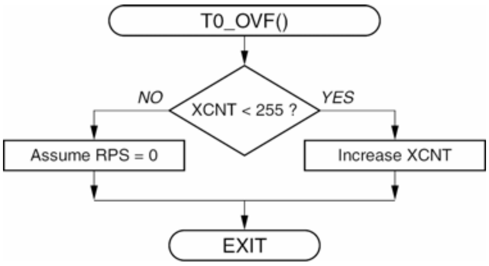


Note that the primary measure of fan speed is recorded in units if RPS (Rotations Per Second), but higher level processing is handled in units of RPM (Rotations Per Minute). This is because RPS readings are always below 100 and therefore nicely fit the data type of unsigned character, but at the end of the day fan performance is usually measured in units of RPM.

3.2.5 Timer 0

The hardware Timer/Counter0 is used as a reference for evaluating the actual speed of the fan. As the timer/counter is only 8 bits in length it does not provide enough resolution for accurately measuring the fan speed over the whole operating range. The hardware timer/counter is therefore extended by software, which can be seen in the pin change interrupt handler, where the hardware timer/counter is read and reset. This works well for moderately high rotational speeds but at lower speeds the 8-bit timer/counter will overflow before a pin change interrupt occurs. For this purpose the timer/counter overflow handler automatically updates the extended software counter, as can be seen in the figure below.

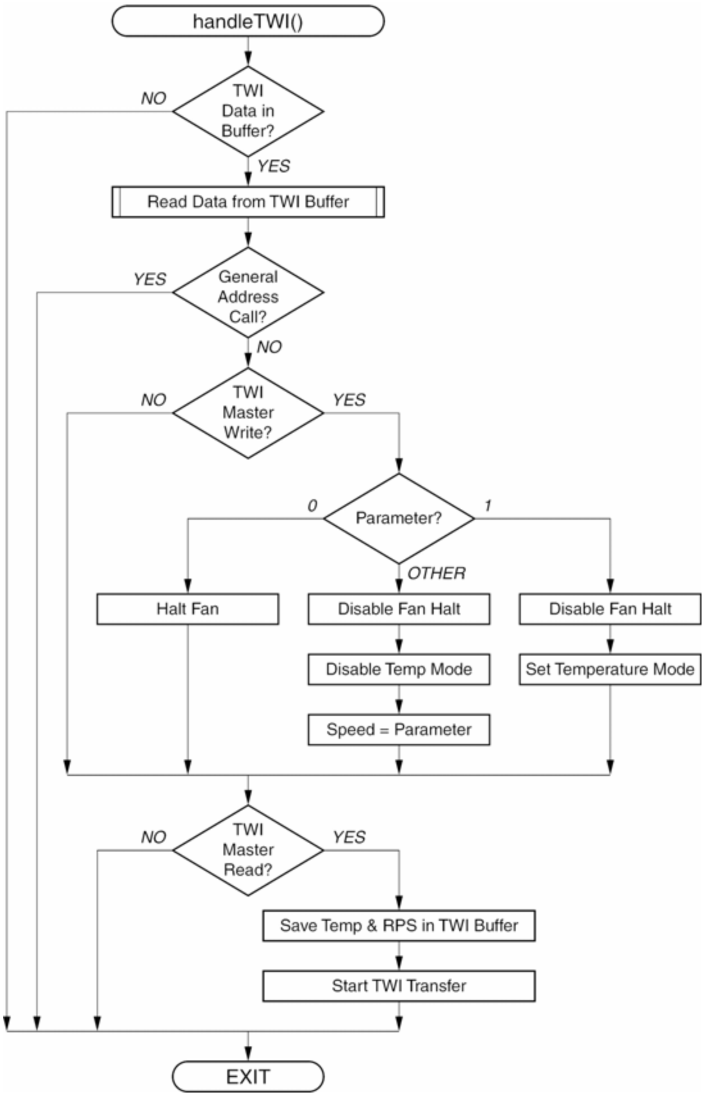
Figure 2-10. Flowchart of Timer/Counter Overflow Handler.



3.2.6 Two-Wire Interface

The fan controller uses the Universal Serial Interface hardware of the AVR to provide an I^{2}C™-compatible Two-Wire Interface. The required software intervention is rather low and mainly consists of preloading variables to be transmitted by the hardware. The flow chart is shown in the figure below.

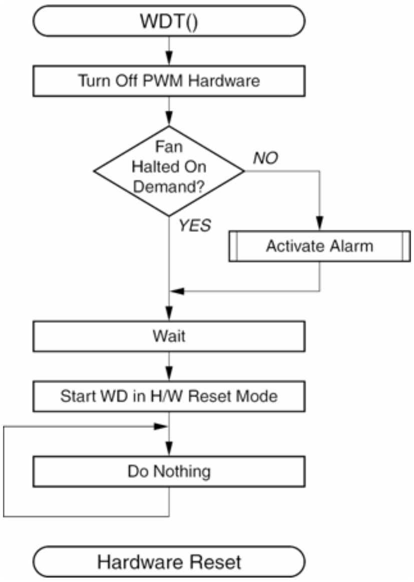
Figure 2-11. Flowchart of Maintenance Routine for Two-Wire Interface.



3.2.7 Watchdog Timer

The watchdog timer interrupt is triggered when the interval of transition signals coming from the Hall sensor exceeds a predefinied time limit. This means the interrupt service routine in the figure below is executed when the fan has stopped or is rotating at a very low speed.

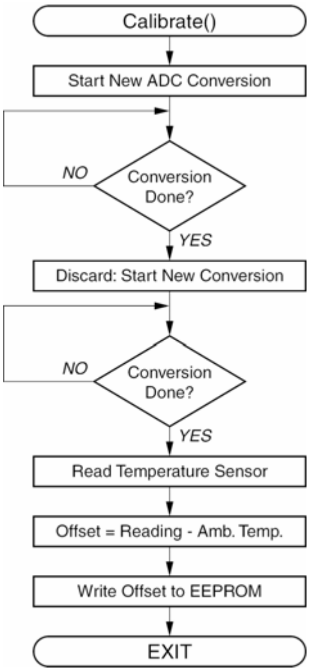
Figure 2-12. Flowchart of Watchdog Timer Interrupt Service Routine.



3.2.8 Calibration

During initialisation the software reads the first location of EEPROM, looking for the TWI address number of the fan. The number returned is assumed valid if it is positive, non-zero and no larger than eight. Else, the software assumes the EEPROM has been erased or is not properly set up and will proceed with device calibration, as shown in the figure below.

Figure 2-13. Flowchart of Calibration Routine.



The calibration routine assumes the ambient temperature is 25 degrees Centigrade and makes a one-point calibration to adjust the offset accordingly. See device data sheet for information on temperature measurement accuracy.

3.2.9 Summary

The table below summarizes the system requirements of the fan controller firmware.

Table 2-5. Statistics of Fan Controller Firmware

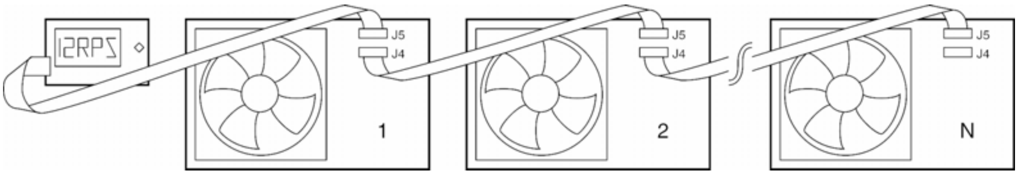
Measure	Debug	Release
Non-Volatile Code Memory (Flash)	2199 bytes	1615 bytes
Non-volatile Data Memory (EEPROM)	66 bytes	66 bytes
Data Memory (SRAM)	95 bytes	95 bytes

The firmware was compiled with IAR Embedded Workbench, version 4.11A.

4 Implementation of Fan Master

In order to test and demonstrate the functionality of the serial bus on the fan controller a fan master has also been constructed. The fan master communicates with one or several fan controllers over a two-wire interface, as illustrated in the figure below.

Figure 2-14. One Fan Master Communicating with N Fan Controllers

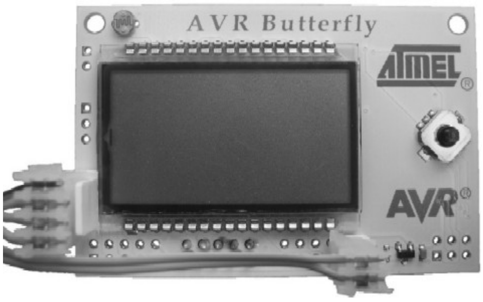


4.1 Hardware

The fan master is a slightly modified AVR Butterfly. The only additions are two pull-up resistors on the TWI bus, a pin header for TWI connection and a pin header for external power supply.

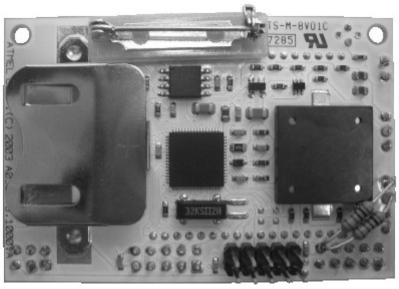
The TWI connector is mounted at J405 (USI Connector) of the AVR Butterfly (see User’s Guide). The external power supply is connected to pins 9 (GND) and 10 (VCC_EXT) of J401 (PORTD connector). Connectors with cables attached are shown in the figure below.

Figure 2-15. Fan Master, Top View



Pull-up resistors for the Two-Wire Interface are readily mounted on the back of the Fan Master. One resistor is soldered between pin 1 (SCL) of J405 (USI) and pin 10 (VCC_EXT) of J400 (PORTB), another between pin 2 (SDA) of J405 and pin 10 of J400. Each resistor should be at least 10 kohm. See figure below.

Figure 2-16. Fan Master, Bottom View



The figure above also shows a mounted J402 connector, which is required for reprogramming the Fan Master. See AVR Butterfly User’s Guide for details.

4.2 Firmware

The firmware of the fan master is based on the AVR Butterfly firmware. Some features have been removed and modifications have been done to implement a menu structure suitable for remote control and monitor of fans. The menu structure is explained briefly in the sections below.

4.2.1 Welcome Message

When the fan master is powered up it will start scrolling the welcome message. Use joystick up or down to change mode.

4.2.2 Scan Mode

Enter Scan Mode by selecting “Scan” on the LCD and pushing joystick rigth or by clicking on the middle of the joystick.

In Scan Mode the fan master will scan the serial interface bus for fan controllers. The scan algorithm cycles TWI addresses 1 through 8, only. For every fan controller found details will be shown briefly, as follows (numerical information may vary):

```
FAN 01
+25 °C
25 RPS
```

Each line will be flashed on the LCD for about one second.

Exit Scan Mode by pushing joystick left.

4.2.3 Single Fan Mode

Enter Single Fan Mode by selecting “Single” and clicking or pushing joystick right.

In Single Fan Mode the fan master will display the same fan information as in Scan Mode but will not scan for other devices. Use joystick left and right to cycle between fan controllers (TWI addresses 1 through 8). The following two lines will be flashed on the LCD if no fan controller is found at the selected address (nn = TWI address):

```
FAN nn
  NA
```

Exit Single Fan Mode by repeatedly pushing joystick left until the message “Single” appears on the LCD.

4.2.4 Remote Control Mode

Enter Remote Control Mode by selecting “Remote” and clicking or pushing joystick right. Then use joystick left and right select one fan controller (TWI address). The display will look as follows:

```
Fn:xx:yy
```

…where n is the fan number (TWI address), xx is the actual rotational speed of the fan (in rotations per second) and yy is the setpoint speed of the fan. When this mode of operation is entered the fan master will read the actual rotational speed of the fan and use that as the default setpoint value.

Use joystick left and right to change fan number (n). Use joystick up and down to change the setpoint value (yy) and watch the actual rotational speed follow (xx). Note that a typical fan saturates at about 50 RPS. Also note that very low speeds may inadvertently halt the fan. When decreasing speed to just a few RPS please allow the fan time to settle before further reducing the speed.

Click joystick to completely stop the fan. The display will now show:

```
Fn:xx:ST
```

Click joystick again to restart the fan. The display will now show:

```
Fn:xx:TM
```

Note that the fan will start in temperature-controlled mode, which means the rotational speed is relative to the ambient temperature of the fan. Move joystick up or down to switch remote controlled mode.

Exit Remote Control Mode by repeatedly pushing joystick left until the message “Remote” appears on the LCD.

4.2.5 Options

To adjust LCD contrast select “Options” and click joystick or push joystick right. The LCD now scrolls the text “Display”. Again, click joystick or push joystick right. The LCD now scrolls the text “Adjust Contrast”. Now click the joystick. Use joystick up and down to change LCD contrast, then click joystick when done. Push joystick left twice to exit.

5 Quick Start

The fan controller described in this document can operate autonomously in stand-alone mode or as a slave, linked to a master.

5.1 Stand-Alone Mode

In stand-alone mode the fan controller works autonomously.

To set up the fan controller in stand-alone mode simply plug the power source to the fan controller boards. Supply voltage should be about 12 VDC and may be connected to either J1 or J15. Polarity does not matter.

The fan will start automatically. In this mode of operation it will constantly monitor the ambient temperature and adjust the rotational speed accordingly. By default, the fan controller tries to maintain the same rotational speed (in rotations per second, RPS) as temperature (in degrees centigrade). For example, at room temperature (25 degrees) the fan should rotate at 25 revolutions per second.

5.2 Slave Mode

In this mode each fan controller works autonomously but is also subject to remote control and monitor by a common master.

Start by connecting one fan controller to the fan master. Use a cable to connect J5 and J16 of the fan controller to J405 and J401 of the fan master.

Several fan controllers can be cascaded to the same serial bus, as illustrated in Figure 2-14. Each serial interface cable may be connected to either J4 or J5 (the connectors are identical). Please note that each fan controller must have a unique TWI address. The address is stored in EEPROM (see firmware description).

Finally, connect power to the controller boards. Supply voltage should be about 12 VDC and may be connected to either J1 or J15. Polarity does not matter.

All fans will start automatically and the fan master will show the welcome message. In this mode of operation each fan performs as in stand-alone mode until addressed by the fan master. The fan master can monitor the rotational speed and ambient temperature of each fan. It can also set the rotational speed of any fan.

5.2.1 Master Firmware

Use the joystick of the fan master to navigate. The menu structure of the master firmware is summarized in the table below.

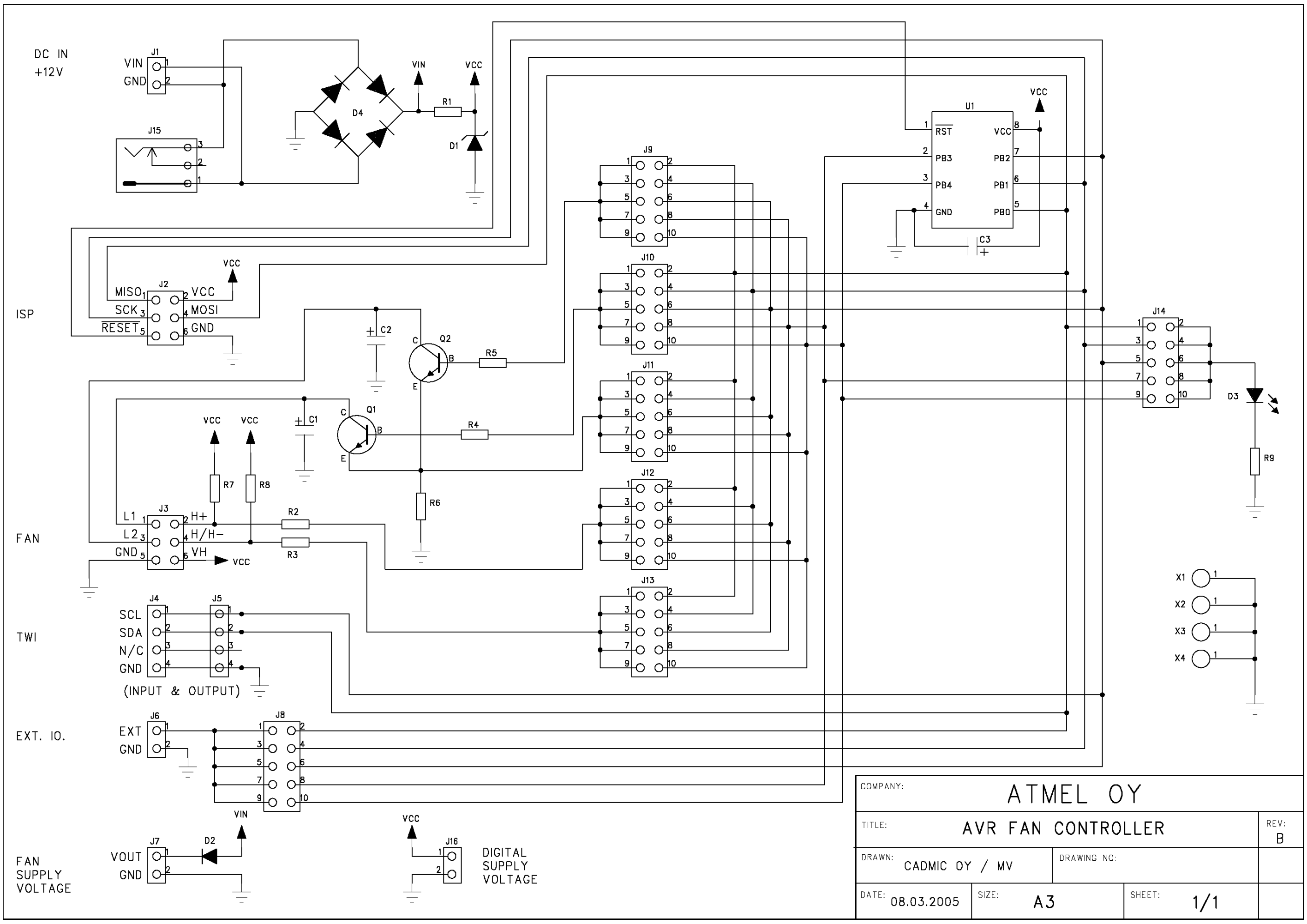
Table 5-1. Fan Master Menu Structure

Menu	Description	Navigation
TITLE	Scrolls welcome message	Joystick up/down to change menu
SCAN	Scans for fan controllers on bus	Push to enter, joystick left to leave
SINGLE	Show data on selected fan controller	Use joystick to look up fans
REMOTE	Set speed on any fan controller	Up/down: speed. Push to start/stop
OPTIONS	LCD contrast adjustment	Joystick up/down to change

6 Appendices

6.1 Schematic

Figure 5-1. Fan Controller Schematic



6.2 Bill of Material

Table 5-2. Bill of Material, Fan Controller

Part	Description	Order Code (1)
C1, C2	Electrolytic capacitor, 2.2 uF, 50 VDC, 2 mm	67-013-20
C3	(optional suppression capacitor)	65-183-69
D1	Zener diode, 4.3 V, 0.5 W	70-053-66
D2	Rectifier diode, 1N4001	70-003-67
D3	(LED, not populated)	75-053-40

Part	Description	Order Code [1]
D4	Bridge rectifier, 1 A, 100 V	70-043-02
H1, H2, H3 [2]	Jumpers, tinned, 2.54 mm	43-710-01
J1, J6	Pin header, straight, 2.54 mm, 1 x 2	43-716-05
J7, J16	Pin header, 2.54 mm, 1 x 2, with friction lock	43-808-61
J2, J3	Pin header, straight, 2.54 mm, 2 x 3	43-717-12
J4, J5	Pin header, 2.54 mm, 1 x 4, with friction lock	43-808-12
J8 ... J14	Pin header, straight, 2.54 mm, 2 x 5	43-717-38
J15	Chassis connector, 2.1 mm, angled	42-051-59
Q1, Q2	NPN Transistor, MPSA06	71-033-69
R1	Resistor, 220 ohm, 0.25 W, carbon film	60-104-17
R2, R7, R9	(not populated)	
R3, R6	Short (tinned copper wire, 0.5 mm)	55-160-34
R4, R5, R8	2.2 kohm, 0.25 W, carbon film	60-105-32
U1	Attiny25 microcontroller	

Notes: 1. ELFA order codes. See www.elfa.se

2. Not shown in schematic

In addition, some miscellaneous parts may be required, depending on the configuration. This includes cables and jumpers, and the actual BLDC motor, of course.

6.3 Printed Circuit Board

Figure 5-2. Silkscreen, top side (outer dimensions 160 x 100 mm)

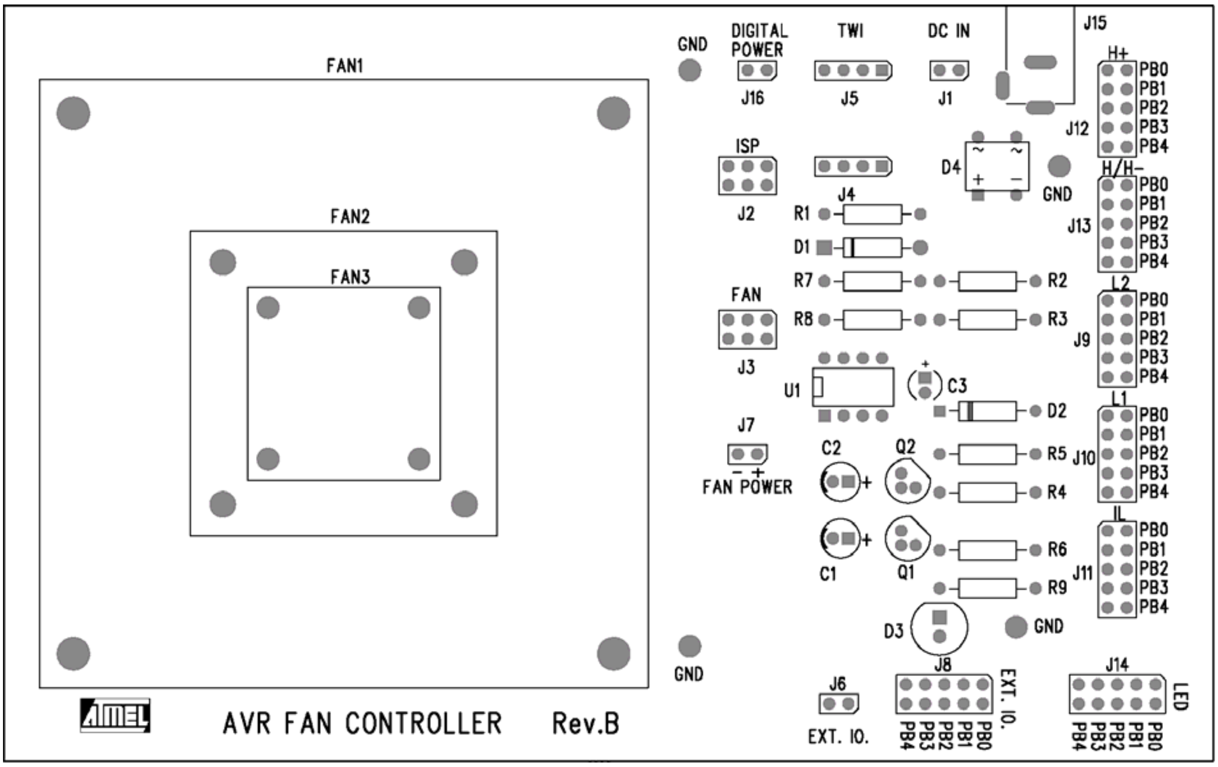


Figure 5-3. Artwork, top side (outer dimensions 160 x 100 mm)

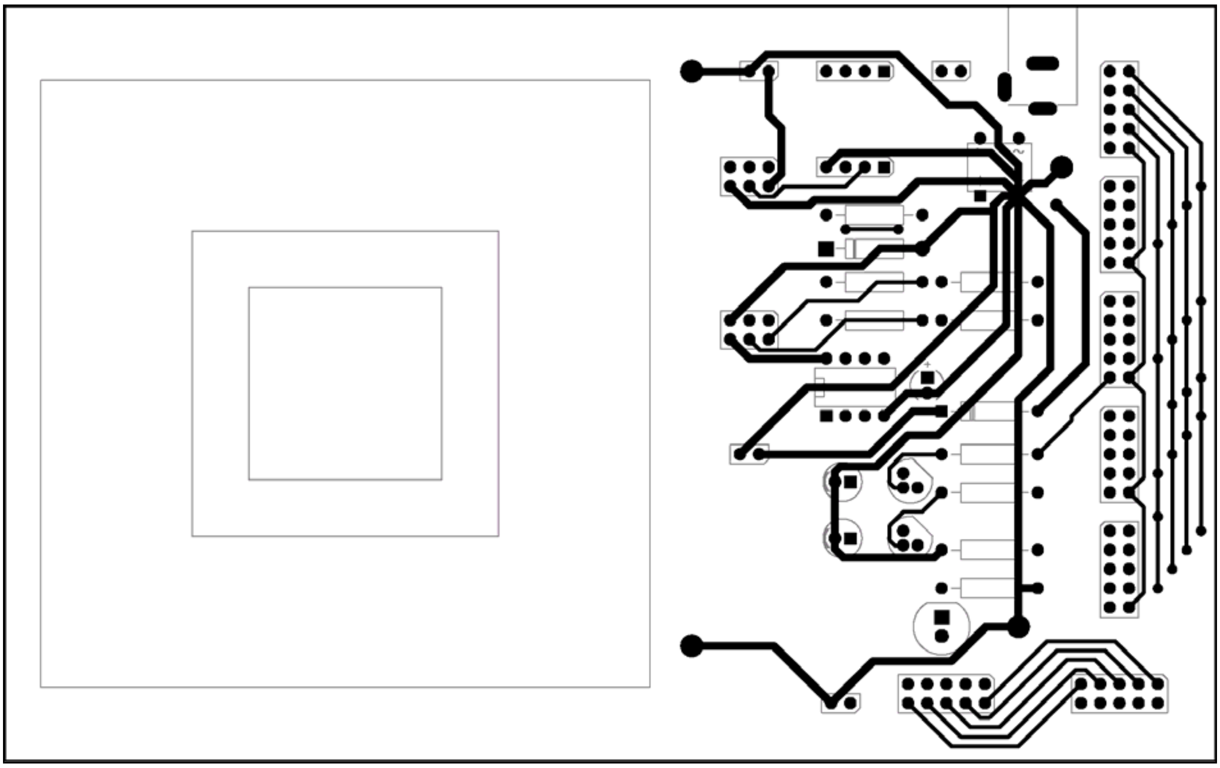
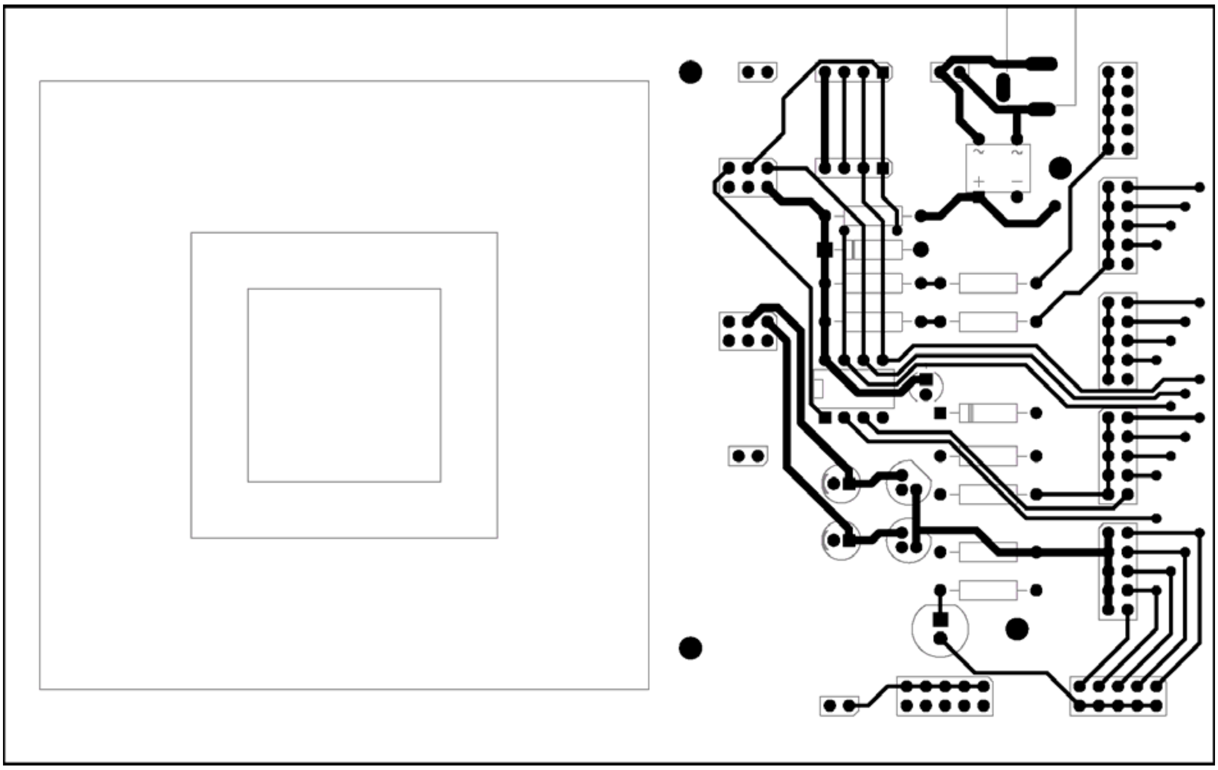


Figure 5-4. Artwork, bottom side (outer dimensions 160 x 100 mm)



7 Table of Contents

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