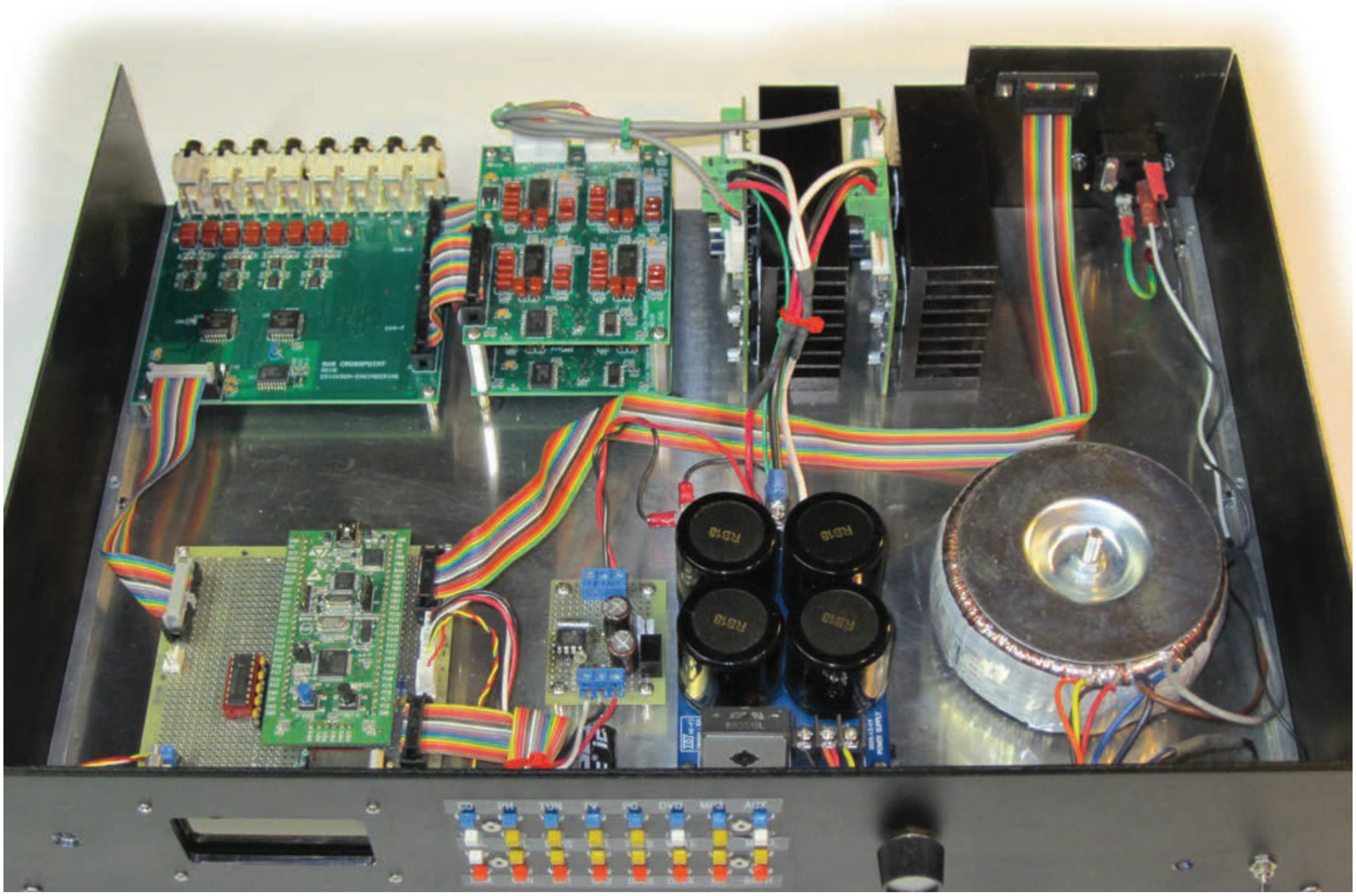

PHOTO 1
Clockwise from the upper left, the whole-house system includes the crosspoint board, two quad preamplifiers, two two-zone stereo amplifiers, an AC transformer, power supplies, and the CPU board with the STMicroelectronics STM32VLDISCOVERY board.

Multi-Zone Home Audio System (Part 1)

Analog Circuit Boards

This multi-zone home audio system enables you to listen to any audio source from anywhere in your home. The modular system uses microprocessor-controlled analog circuitry. Its controls include a front panel with a simple LCD-based GUI, an IR remote control, and a keypad for each zone.

By Dave Erickson (USA)

I have built my own audio equipment since I was an EE graduate in the mid 1970s. At my first real job at HP Medical, engineers were allowed to use engineering lab-stock components to build home projects. However, good commercial stereo gear was not free. In those days I had limited dollars. Money spent on gear competed with money spent on rent and food. I began designing and building amplifiers, preamplifiers, mixers, and speakers and still do, 36 years later.

Recording LPs to cassette tape was popular in the 1970s, so for a home preamplifier I designed a second output bus that could be independently selected from the main listening bus. At the time, this ability appeared only on high-end audio gear. For source selection, instead of using mechanical switches, I used digitally controlled CMOS analog switches and two rows of illuminated momentary push buttons to select the two outputs. I soon realized that the second bus could be used to send different audio to another room and the seed of a multi-zone system was planted.

FIRST-GENERATION SYSTEM

In the early 1990s, I developed C microprocessor code on Freescale MC68HC11

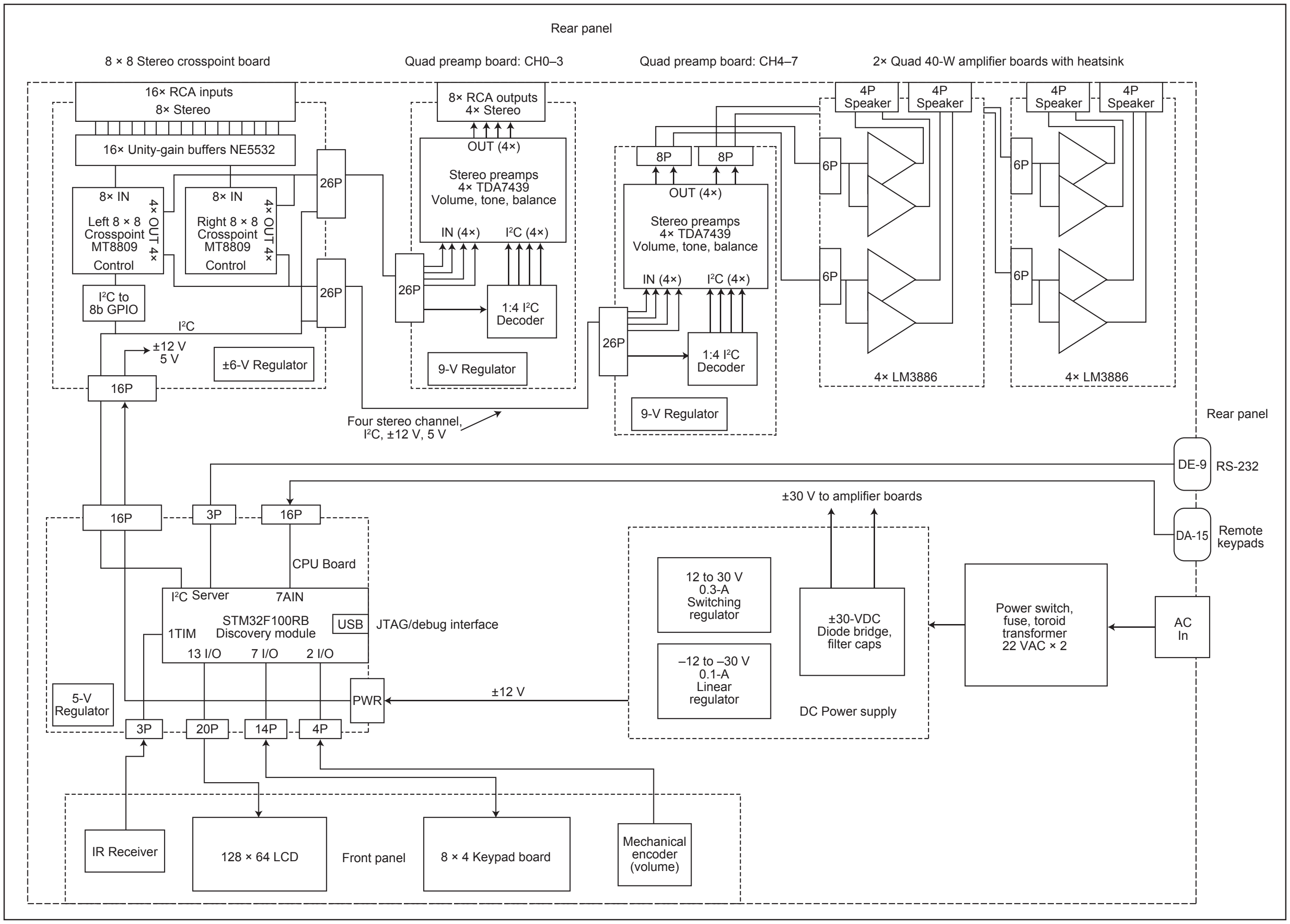

FIGURE 1

The system block diagram shows the boards, controls, amplifiers, and power supplies.

microprocessors and used it to build my first multi-zone audio system. The system had an 8 × 8 stereo crosspoint capable of selecting a different source for each of the eight zones and up to eight stereo preamplifiers, each with volume and tone controls. The status was displayed on a graphic LCD and could be controlled by front-panel switches, an IR remote, remote keypads in each zone, or by RS-232.

I used this system for more than 15 years and was satisfied with its ability to send different sounds to the different rooms in my house as well as the basement and the deck. But the system needed an upgrade.

IR remotes went obsolete, so the IR codes needed to change. The system was 90% hand-wired and pretty messy. The LCD and several other parts became obsolete and the C development tools had expired. Processors had evolved to include flash memory and development tools evolved beyond the old burn-and-pray method. I had used an assortment of prototypes and yard-sale amplifiers and receivers for the amplifiers. After 15 years, the system had become an important part of our home and was here to stay.

STM32 2011 DESIGN CHALLENGE

Photo 1 shows my whole-house system. My goal was to build a modern, smaller, cleaner, and more efficient system. I decided to upgrade it with a recent processor and LCD and to use real PC boards. I was considering several processors, one of which was the STMicroelectronics STM32VLDISCOVERY board, which I had picked up for free at the 2011 Embedded Systems Conference in Boston, MA.

STMicroelectronics had announced a design competition based on the STM32F processors. In addition to offering the STM32VLDISCOVERY board, STMicroelectronics teamed with Atollic and others to offer free evaluation compilers. I had begun to block out the design and lay out the analog boards, but had not yet selected a processor. I decided to use something from the STM32 family and hoped the contest deadline would be a good motivator. The puzzle pieces were beginning to fit together.

The 2011 contest deadline approached and I still had not ordered PC boards. Fortunately, STMicroelectronics pushed the deadline for the proof-of-concept out one week. Fueled by caffeine and pizza, I spent a week of long nights stuffing boards and writing code. I was

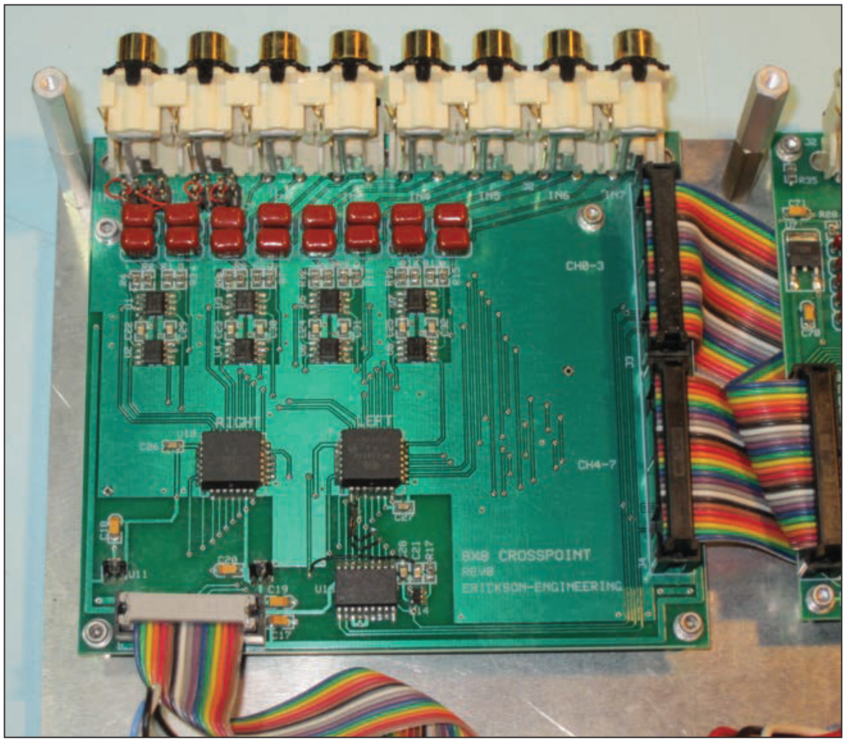

PHOTO 2
The crosspoint board shows the RCA input jacks (top), ribbon cable connections to the quad preamplifiers (right), and control and power cable from the CPU (bottom). Rev0 has a few black wires (lower center).

able to demo the prototype and ultimately won one of three second-place prizes. STMicroelectronics's excellent libraries and examples helped me get the complex ARM Cortex-M3 peripherals working quickly.

Choosing the STM32F100 processor was a bit of overkill, but I hoped to later use it to add future capabilities (e.g., a web page and Ethernet control) and possibly even a simple music server and audio streaming.

In the first part of this article series, I will delve into the design's audio sections. In Part 2, I'll discuss the digital CPU, the various controls, and possible future plans. A full set of hardware and software documentation is available on *Circuit Cellar*'s FTP site.

SYSTEM OVERVIEW

Figure 1 shows the system design including the power supplies, front-panel controls, and the audio and CPU boards. The system is modular, so there is flexibility in the front-panel controls and the number of channels and amplifiers. My goal was to fit it all into one 19″, 2U (3.5″) high rack enclosure.

The CPU board is based on a STM32F100 module containing an Cortex-M3-based processor and a USB programming interface. The CPU receives commands from a front-panel keypad, an IR remote control, an encoder knob, RS-232, and external keypads for each zone. It displays its status on a graphic LCD and controls the audio circuitry on the crosspoint and two quad preamplifier boards.

Photo 2 shows the crosspoint board, which is the analog heart of the system. It receives line-level audio signals from up to eight stereo sources via RCA jacks and routes audio to the eight preamplifier channels located on two quad preamplifier boards. It also distributes digital control and power to the preamplifiers. The preamplifier boards can either send line-level outputs or drive stereo amplifiers, either internal or external to the system.

My current system uses four line-level outputs to drive PCs or powered speakers in four of the zones. It also contains internal 40-W stereo amplifiers to directly drive speakers in the four other zones. Up to six stereo amplifiers can reside in the enclosure.

STEREO CROSSPOINT

The crosspoint provides a way to route analog audio signals from the eight sources to the eight zones. Because all the audio passes through this board, the design goals were low distortion and noise, low channel-to-channel crosstalk, and no audible digital crosstalk. The low crosstalk requirement is to prevent loud music in one zone from disturbing quiet passages in another.

CMOS switches are economical and digitally controlled, but they are fairly nonlinear. Look at most CMOS switch datasheets, such as the Texas Instruments 74HC4051, and you will see curves of switch On resistance vs. signal voltage. With line-level input signals (approximately 1 V_{RMS} or 2.8 V_{PP}) and a typical load resistance, this variation leads to harmonic distortion. To clarify, for distortion you shouldn't be concerned with the switch resistance, but with the change of switch resistance over the expected signal voltage range.

A rough approximation to determine the amount of distortion is to use the ratio of the switch resistance change to the load resistance. For example, if a switch varies 10 Ω over the expected 2.8-V_{PP} input and the load is 100 kΩ, the distortion is about 10/100 kΩ or a respectable 0.01%.

This rule of thumb doesn't take into account high-frequency effects of capacitive loads. Note that for CMOS switches, the curves are flatter with higher supply voltages, so you should use the highest supply voltage possible. I used Microsemi MT8808 analog crosspoints, which specify 0.01% distortion (typical) even when driving a 1-kΩ load.

Channel-to-channel crosstalk is determined by the switch On resistance and an offending channel's Off capacitance. This type of crosstalk increases linearly with frequency. You want to minimize the switch and the source output resistance. Using a low-impedance op-amp to

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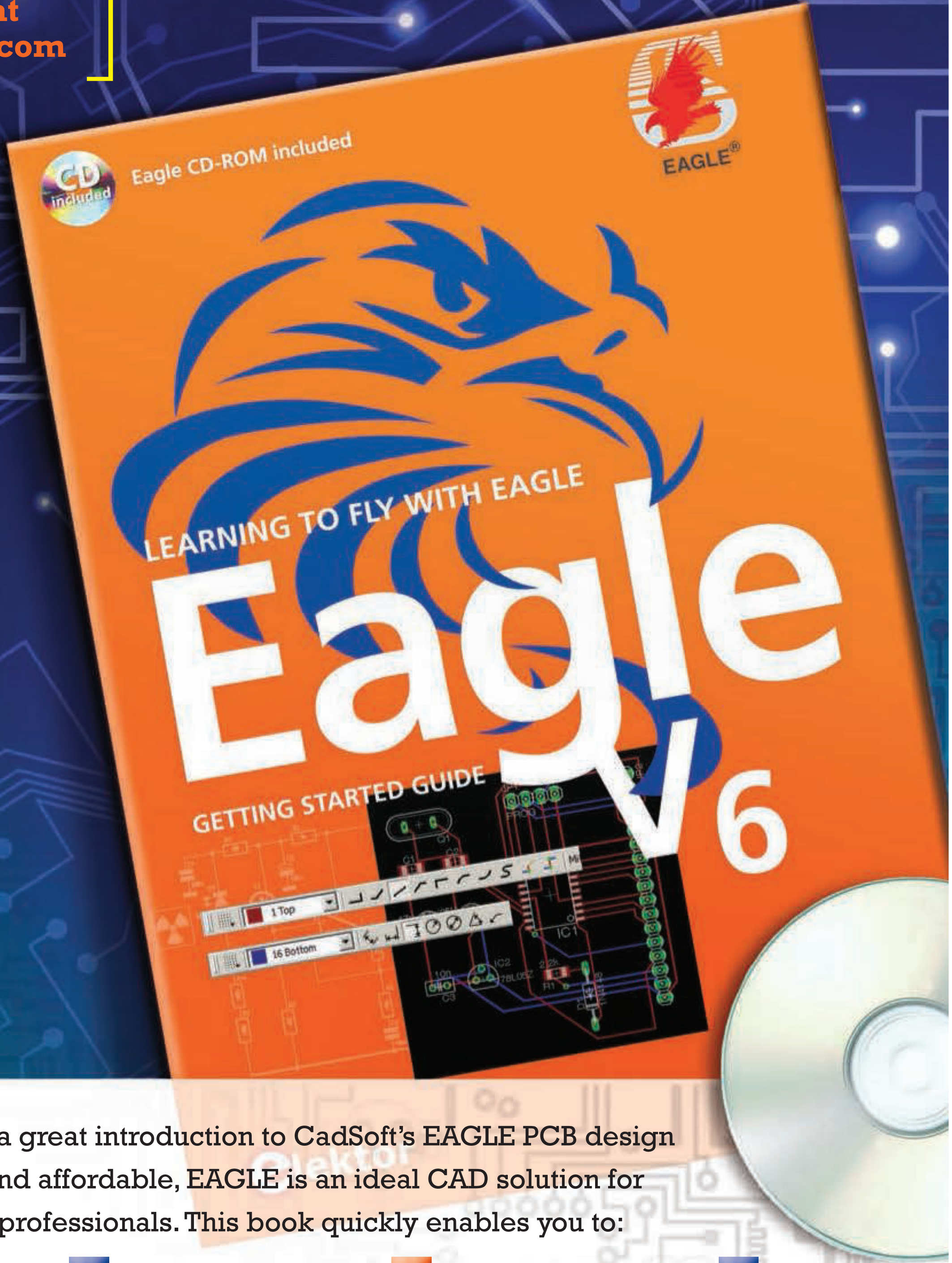

Learning to Fly with EAGLE is a great introduction to CadSoft's EAGLE PCB design software. Powerful, reliable, and affordable, EAGLE is an ideal CAD solution for enthusiasts and engineering professionals. This book quickly enables you to:

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- Understand how EAGLE relates to the stages of PCB manufacturing
- Create a complete project, from design through PCB fabrication

drive the switches reduces crosstalk.

In summary, use low-resistance switches at the highest supply voltage possible, drive the switches with low impedance, and load them with high impedance. I used MT8808 8 × 8 CMOS crosspoints in a 44 plastic leaded chip carrier (PLCC) package. Two of these devices provide 8 × 8 stereo, one each for the right and left channels. One MT8808 could also be used as a 4 × 4, two-channel crosspoint. These parts cost about $9 each. They can be powered by up to 13.2 V maximum and the eight control pins are 5-V CMOS-compatible.

The MT8808 contains a matrix of 64 individual switches arranged as eight rows and eight columns, with the columns as inputs and the rows as outputs. For this application, you want only one switch per row (output) on at a time, or an input channel can be shorted to another through the switch. So, before turning on a source

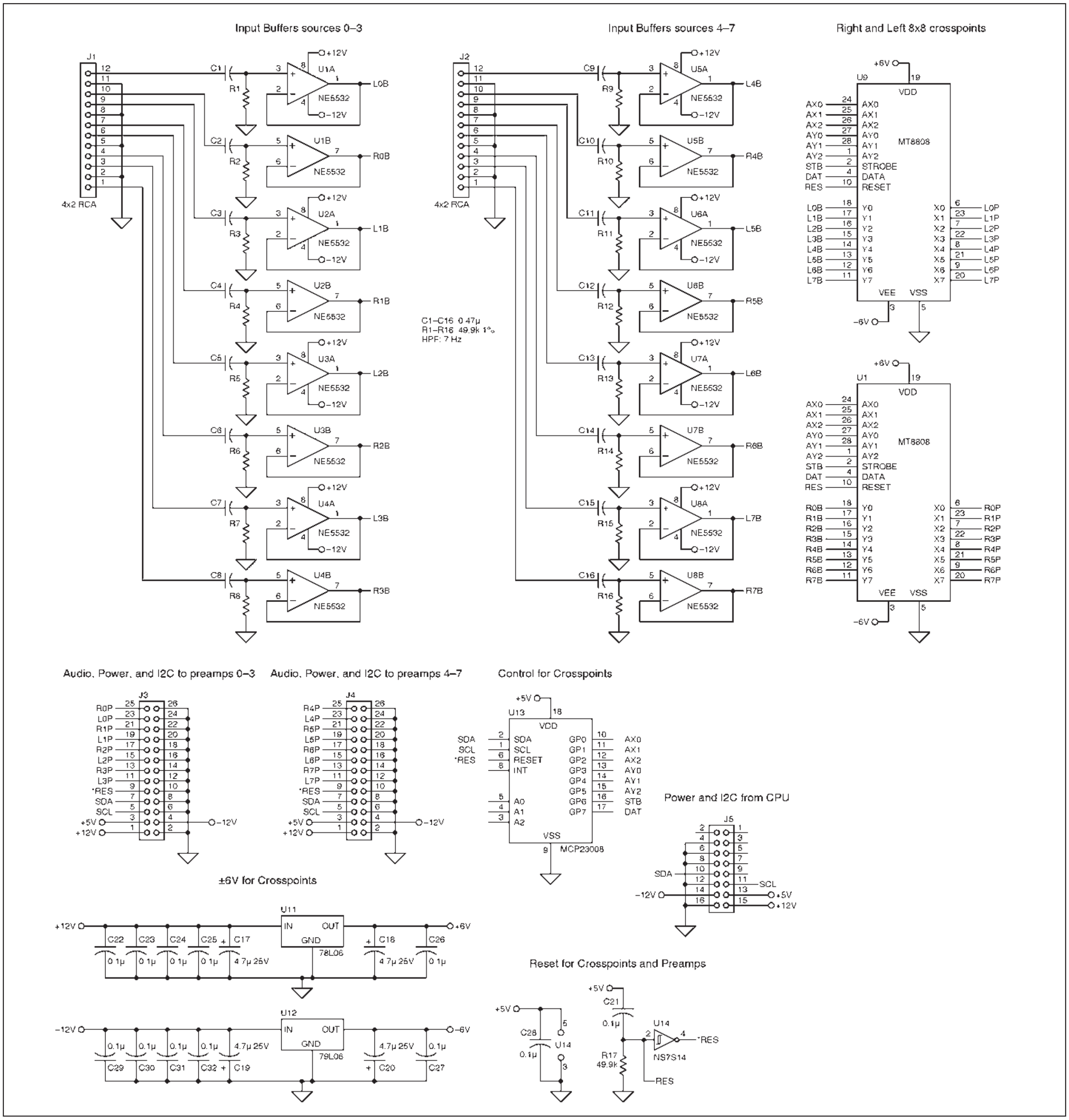


FIGURE 2

The crosspoint board schematic shows the input buffers, crosspoint chips, I²C controls, and power supplies.

switch, always turn off the previous source. Keep the previous channel in CPU memory for this purpose.

CROSSPOINT BOARD

Figure 2 shows the crosspoint board schematic. The MT8808 control interface consists of three-row (X) and three-column (Y) address bits, one data On/Off bit, and a strobe. There is also a CS, which is tied low and a Reset, which is pulsed low at power-up to ensure all the switches are initially off.

I used an I^{2}C bus for the other audio controls in the system and used a Microchip Technology MCP23008 I^{2}C-to-GPIO chip to drive these eight control signals. The right and left channels are identically controlled, so both MT8809s receive the same eight control signals.

The firmware to set one crosspoint output requires the following steps: First turn off the previous switch. Next set the previous address row and columns, set strobe = 1, and set strobe = 0. Then turn on the new switch, set the new address row and columns, set strobe = 1, and set strobe = 0.

With the MCP23008, this operation requires one command byte followed by six data bytes. With an I^{2}C clock of 400 kHz and about 10 bit times per byte, this takes 175 µs.

The crosspoint receives digital control from the CPU board, receives external audio signals, and distributes audio signals to the preamplifier boards and then on to the amplifiers. It was convenient to use this board to distribute the control signals and the power supply voltages to the preamplifier channels. I used 0.1" dual-row ribbon cables to simplify the wiring. These are low-cost and easy to build.

To transmit high-quality audio along with power and logic control signals on the same cable, it is important to use a lot of grounds. Two 34-pin cables each connect to a quad preamplifier board. In each of these cables, four channels of stereo audio are sent with alternating signals and grounds. The alternating grounds act as electric field "guards" to reduce crosstalk. There are just two active logic signals: I^{2}C clock and data. Power supply voltages (±12 and 5 V) are also sent to the preamplifiers with multiple grounds to carry the return currents.

I used a similar grounding/guarding approach throughout the design to minimize crosstalk, both from channel to channel and from digital to analog. On the two-layer boards, I used ground planes on the bottom layer. Grounded guard traces or ground planes are used on the top layer. These measures minimize the capacitance between analog traces and thus minimize crosstalk.

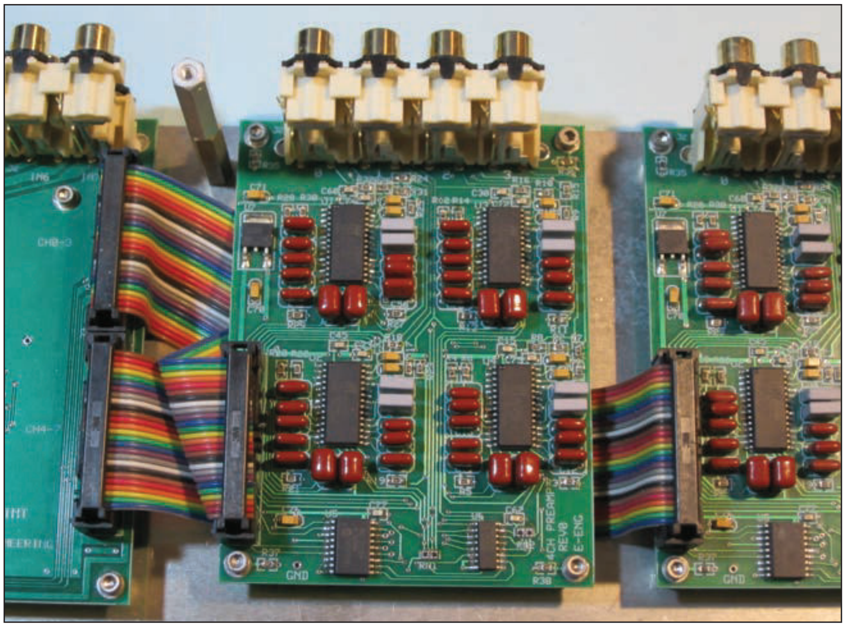


PHOTO 3
Two of the quad preamplifier boards connect to the crosspoint via 34-wire ribbon cables.

The digital and I^{2}C signals are physically separated from analog signals. Where they need to be run nearby, they are separated by ground planes or guard traces.

The audio input buffers use eight Texas Instruments NE5532 dual audio op-amps

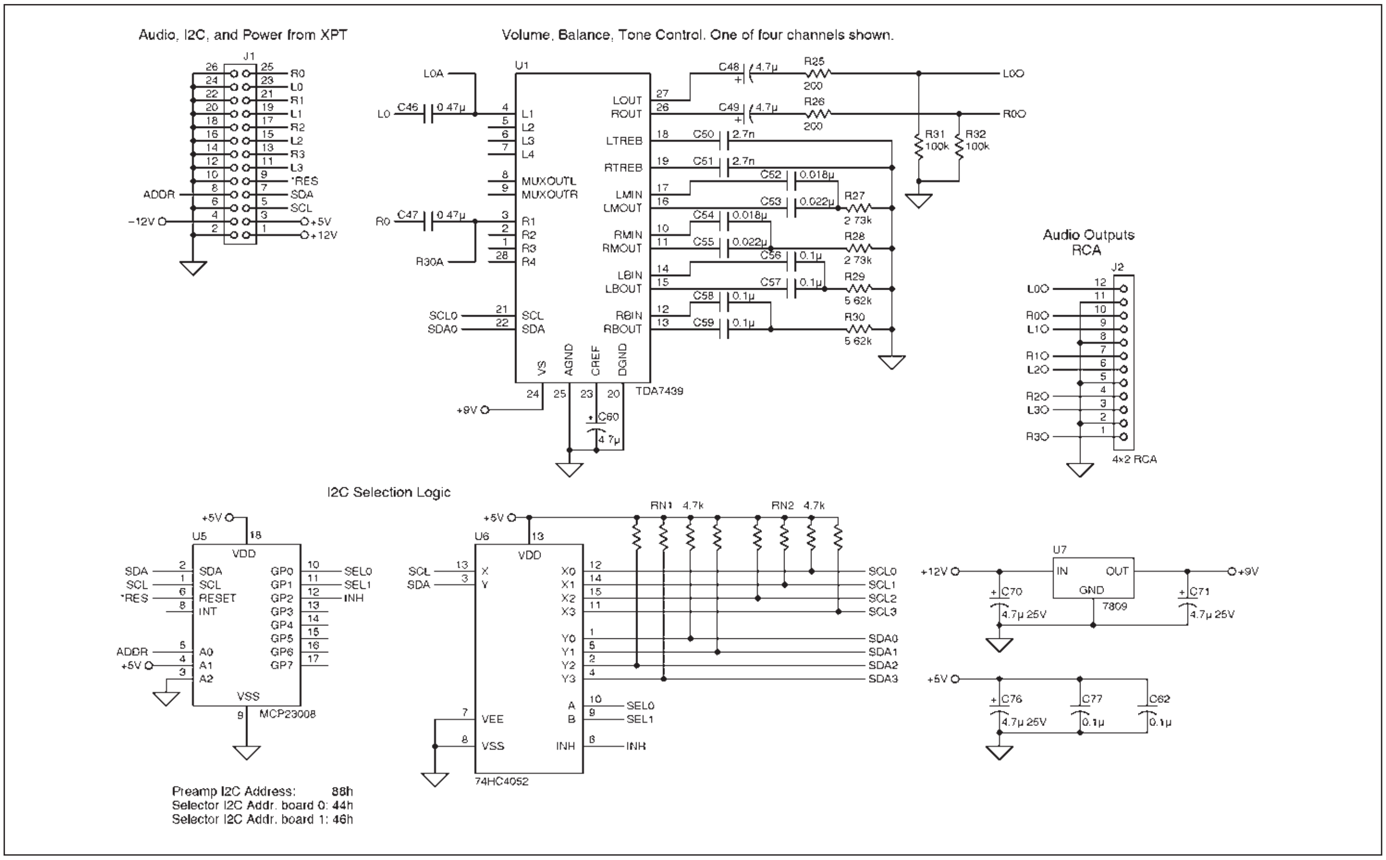
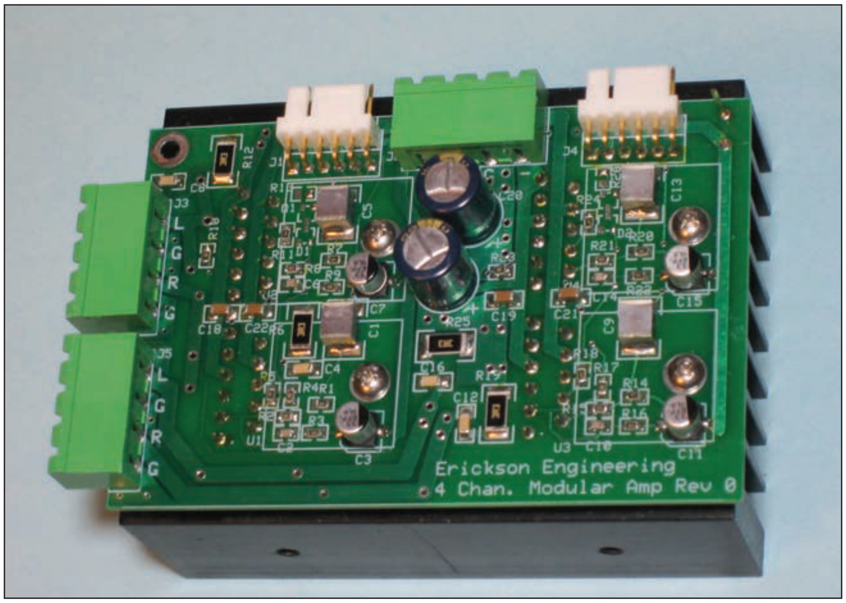


FIGURE 3

The quad preamplifier board schematic diagram includes preamplifiers, the I²C demultiplexer, the 9-V power supply, and one of the four preamplifier channels.

PHOTO 4

The four-channel amplifier board and heatsink are shown. Speaker connections are on the left and power and input connections are on top. The four Texas Instruments LM3886 amplifier chips are sandwiched between the board and the heatsink.



powered from ±12-V supplies. These are high-quality, low-cost, low-noise amplifiers with less than 0.01% distortion. They use the standard SO8 pinout, so other parts can be substituted. All audio coupling capacitors are designed with 10 Hz or lower high-pass cutoff. I used polyester film capacitors to minimize low-frequency distortion that can be caused by Tantalum or ceramic capacitors.

I used Switchcraft stacked RCA jacks for audio input and output connections. These provide a 4 × 2 array of jacks and are color coded (red for right). I used two of these arrays to provide the eight stereo inputs to the crosspoint. One array provided the four line-level outputs of the quad preamplifier boards. Voltage regulators 78L06 and 79L06 provide the ±6-V power to the crosspoints. A simple power-on reset circuit properly initializes the crosspoint chips.

I used ExpressPCB schematic and board layout software to layout and build all the PC boards. I use ExpressPCB for boards when I want small quantities of boards quickly and at low-cost.

QUAD PREAMPLIFIERS

Photo 3 shows the quad preamplifiers and **Figure 3** shows the preamplifiers' schematic. My goal for the preamplifiers was to have independent volume, balance, and tone controls for each channel. Good muting capability guarantees that when a channel is off, it is really off (i.e., not only a total lack of sound, but also a lack of noise). Most channels feed full-gain (26-dB) power amplifiers and

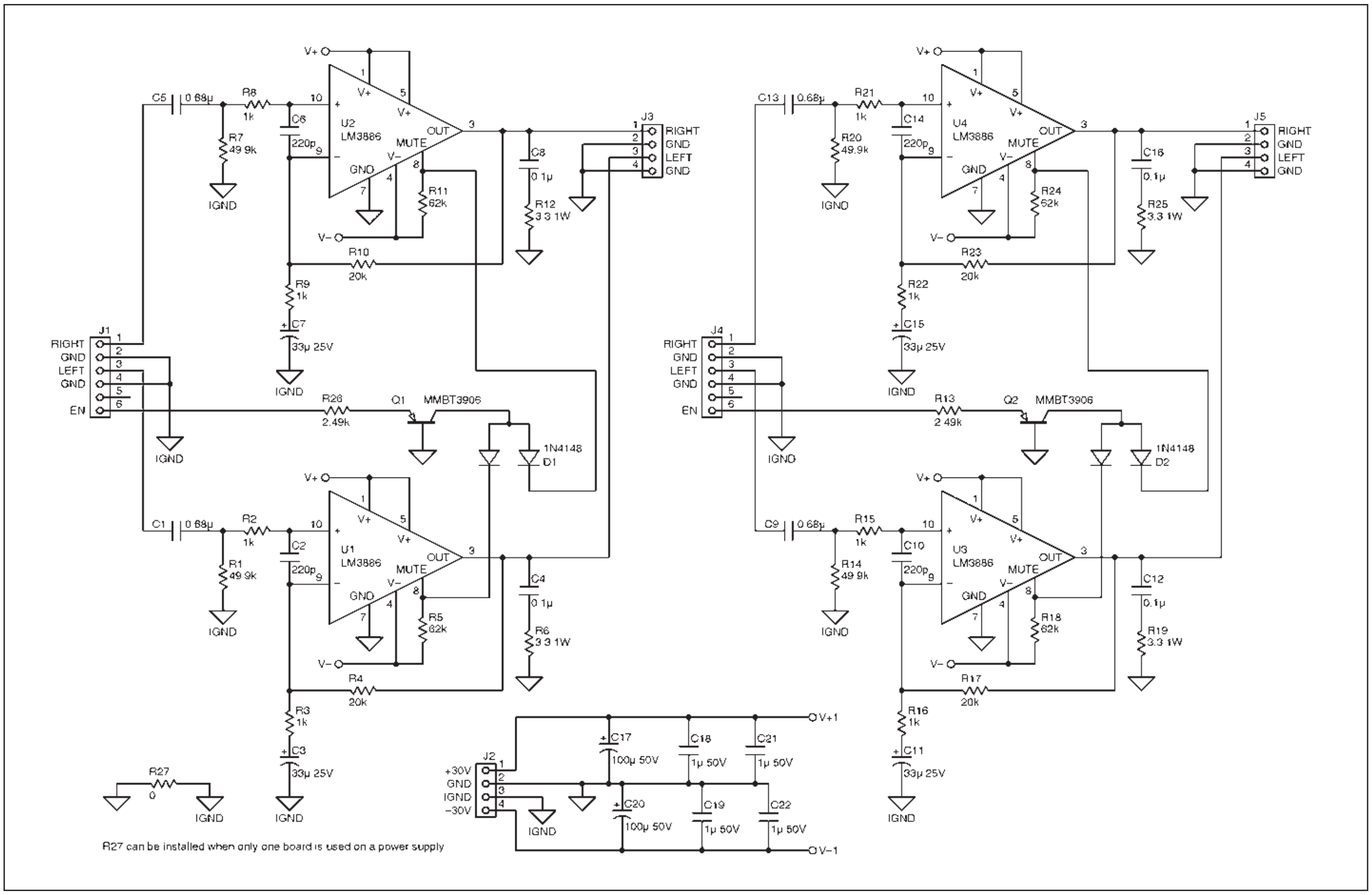


FIGURE 4

The four-channel Texas Instruments LM3886 amplifier schematic includes separate IGND and GND to reduce crosstalk.

efficient speakers, so any preamplifier noise can be heard. Clean sound (low distortion) is also important.

I used STMicroelectronics's TDA7439D preamplifiers. These I²C-controlled devices are designed for home and car audio systems and have good performance and excellent muting. They offer controls for bass, midrange, and treble, but not loudness. Loudness compensation, which is an increase in bass and treble at low volume, could be approximated in software by boosting bass and treble at low volume settings.

The TDA7339 has three sets of level controls: main volume, independent left and right speaker controls (used for balance), and an input level. The main volume controls have 0 to 40 dB of range in 1-dB increments, which I found provided inadequate low-volume control range. So when the volume is set below −40 dB, I kick in additional speaker attenuation. My software currently has 60 db of volume range in 2-db increments, which works well. The audio controls are accessed through simple I²C commands to registers.

Building four channels on two small quad preamplifier boards was a convenient way to partition the desired eight preamplifier channels and to enable a smaller, four-zone system to be built. The input coupling and tone filter capacitors are film types. The output coupling capacitors need to be large values due to the lower amplifier input impedances. Typical amplifier input impedance is about 10 kΩ. I used tantalum capacitors. The preamplifiers are powered from a 9-V linear regulator.

Most audio preamplifier ICs don't have a provision to address multiple units on an I²C bus. Therefore, an external demultiplexer was required to enable each of the eight identical preamplifiers to be addressed. The select control logic uses a MCP23008's output to select one preamplifier I²C bus via a dual 4:1 analog Texas Instruments 74HC4052 multiplexer, which routes SDA and SCL to each preamplifier.

To enable two identical quad preamplifier boards to be used without jumpers for addressing, a signal ADDR on the 34-pin connector is wired low for the first quad preamplifier board and high for the second board by the crosspoint board. ADDR is then used to give the MCP23008 on each quad preamplifier a unique I²C address. This way, eight preamplifiers on two boards can be selected without using jumpers.

When building a multiboard I²C system, system configuration is an issue, particularly during board bring up. When an I²C access to a nonexistent device occurs, the STMicroelectronics I^{2}C functions simply hang waiting for the I^{2}C acknowledge bit. If you are debugging code, you can halt and determine which device caused the problem. But if you do not have one of the boards connected, it is undesirable for the system to hang. The code should include a proper timeout and error handling.

For now, I simply use a configuration variable to specify the number of channels installed and recompile when the hardware configuration is changed. It's not very elegant, but it works.

MODULAR AUDIO AMPLIFIERS

It was challenging to package eight or 12 audio amplifier channels in a small enclosure. One challenge was using a single large power supply to power all the channels. Another was building a compact and modular package for the amplifiers. I have used the popular Texas Instruments LM3886 amplifier for several projects in the past and like its sound, ease of use, and low cost.

The electrical design challenge is that if you simply connect one power supply to multiple audio amplifiers the amplifiers will crosstalk to the tune of −40 dB. At this level, crosstalk will be audible. It is caused by having a common ground return for the supplies to the power supply, as well as common input grounds.

Speaker current of an aggressor-channel causes IR drops in the power ground return. Some of this IR drop is then imposed on all the other channels' input grounds. It then gets augmented by the amplifiers' 26-dB gain and results in crosstalk.

I struggled with this for a while and finally built a SPICE model that included estimates for wire resistance. Sure enough, the simulation showed that crosstalk was problematic. The solution was to separate the input and feedback grounds from the output (speaker) returns. This reduced the crosstalk from an unacceptable −40 dB to a much quieter −80 dB, which is perfect.

The next challenge was how to package several LM3886s on a small board with a heatsink. The LM3886 11-pin TO-220 package is intended to be mounted to a heatsink surface at a right angle to a PC board. This takes up quite a bit of space.

I chose to rebend the LM3886's leads and mount it, the board, and the heatsink all in parallel with the four LM3886s sandwiched between the heatsink and the board (see **Figure 4**). This approach used much less space and enabled four amplifiers to be built on an ExpressPCB MiniBoard which is 3.8" × 2.5" I was lucky to find surplus heatsinks online that perfectly fit the board. **Photo 4** shows the result, which is a compact package.

I used a 140-W, 22-VAC toroidal transformer for the amplifiers' ±30-VDC power supply. A rectifier/filter board converts the 2 × 22 VAC to ±30 VDC. I used a CUI V7812-500, which is a 7812 replacement, to build a small 30-to-12-V, 0.5-A switcher to power the preamplifier circuitry.

The –12 V at 100 mA can be derived from the 12 V by a charge pump with a lot of output capacitance or from a Texas Instruments 7912 linear regulator. The –12-V load is about 80 mA, all on the crosspoint board. A linear regulator will dissipate 1.44 W (i.e., 30 – 12 × 0.08), so a small heatsink should be used. The 5 V is generated via a linear regulator from 12 V on the CPU board.

I did make a bit of a mistake on the amplifier design. The LM3886 has a Mute pin, which I incorrectly assumed would reduce quiescent power consumption. But alas, it only mutes the audio. Each amplifier always draws 50-mA quiescent current, and with ±30-V power supplies, that results in 3 W (i.e., 60 V × 50 mA) per amp. With eight amps on two boards in a small space, 24 W of quiescent power causes excess heat. Twelve amps (six zones) would be worse. The system is almost always on, so the amps are always hot.

There is no easy way to power down an LM3886. A fan would keep them cool, but 24 W of standby power is far too much, and I

PROJECT FILES

circuitcellar.com/ccmaterials

RESOURCE

Atollic, www.atollic.com.

SOURCES

Cortex-M3 processor
ARM, Ltd. | www.arm.com

V7812-500 Output current
CUI, Inc. | www.cui.com

MiniBoard PCB
ExpressPCB | www.expresspcb.com

MC68HC11 Microprocessor
Freescale Semiconductor, Inc. | www.freescale.com

MCP23008 I^{2}C to GPIO
Microchip Technology, Inc. | www.microchip.com

MT8808 Analog crosspoint switch
Microsemi Corp. | www.microsemi.com

Visio diagramming and vector graphics application
Microsoft Corp. | www.microsoft.com

STM32VLDISCOVERY board, STM32F100 processor, TDA7439D preamplifier, and STA540 power amplifier
STMicroelectronics | www.st.com

74HC4051 CMOS, 74HC4052 multiplexor, LM3886 amplifier, 7912 linear regulator, and NE5532 op-amp
Texas Instruments, Inc. | www.ti.com

ABOUT THE AUTHOR

Dave Erickson (dave@djerickson.com) has been an electronics hobbyist since the 1960s. He earned his BSEE in 1976. Dave worked at HP Medical, Datacube, Analogic, Zoll Medical, Teradyne, and numerous startups. He currently develops electro-optic and ultrasound systems for a cardiac catheter system at Infraredx. Dave's electronics interests include instrumentation, audio, electronic music, and boat electronics. He also enjoys biking and sailing. His projects are available at www.djerickson.com.

don't want to listen to a fan. I considered switching the DC power to pairs of amplifiers via power FETs, but eventually found other amplifier chips (e.g., an STMicroelectronics STA540 amplifier) that use less power, are lower cost, and provide a low-power standby function.

The next revision will address this issue, someday. For the final cooling solution, I plan to use a quiet 80-mm fan, which will turn on only when the internal temperature rises above a threshold. My thinking is that if it is loud enough in the house to heat the amplifiers, the fan will not be heard.

PACKAGING

To have the system in the living area of my house, there is an implicit approval process by the aesthetic committee with whom I live. However, I do have a bit of leeway inside the stereo cabinet. I chose to use 19″ rack mount hardware, all in black. Most consumer stereo equipment is black and is about 17″ wide, the same width as rack equipment without the rack mounting tabs. I chose 2U (3.5") height, which provides room for the boards and the front and rear panel components. Only the amplifier modules come close to this height inside.

A 12″ depth enabled everything to fit with room to spare. Some off-the-shelf enclosures have these dimensions, but I have not found one I like. I used a standard 0.25″ black aluminum rack panel for the front and cut individual sheets of 0.060″ aluminum for the other parts. I used 12″ long 0.25-in^2 aluminum extrusion stock for the four inside corner braces. This material can be drilled and tapped for removable 4-40 screws or drilled and pop riveted for permanent mounting. Tapped 6-32 holes in the extrusion ends provide front and rear panel mounting. Black screws on black sheet metal are less visible than silver screws.

For the finish on the other parts, I like black semi-gloss spray enamel. I tried to find time on a Bridgeport machine to make the front-panel LCD and keypad button holes close to the desired dimensions. I used a bandsaw to cut the other sheet metal parts and file the edges smooth.

I used a combination square and scriber to mark the holes for the layout. A drill press enables more precision than a hand drill. I used Microsoft Visio diagramming and vector graphics application to design the case. Its dimensioning features make it a reasonable tool for simple 2-D CAD drawings. (Yes, I know real CAD tools are available.)

The rear panel requires 24 holes that need to perfectly align with the RCA jacks on two boards, four speaker connectors, a few other connectors, and cooling holes. I have not yet tackled this task, so the system currently has only a partial rear panel and no top panel. This helps prevent people from mistaking it for a store-bought system.

In Part 2, I will discuss the home audio system's CPU, development tools, controls, firmware, and future plans.