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Advanced Power Electronics Term Project

Stepper Motor Controller

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Introduction

This paper analyzes the power electronics and control of a stepper motor circuit and its power supply. The four components of interest are a DC/DC converter, a microcontroller, three stepper motor controllers, and the stepper motors themselves. The DC/DC converter is a LM2576-5V IC, the microcontroller is an Atmel AT-Mega 128, the stepper motor controllers are A3977SEDs, and the stepper motors are 2-phase bipolar stepper motors.

The DC/DC converter converts a 24V DC input to 5V DC and supplies power to the microcontroller, stepper motor controllers, and other components. The microcontroller controls the signals to the stepper motor controller. The stepper motor controller then controls the power, direction, and speed of the stepper motors.

Stepper Motors

A stepper motor is different from a regular motor; it steps through rotations as opposed to spinning continuously through rotations. A stepping motor has some advantages and some disadvantages to regular motors. An advantage is discrete steps, hence stepper motor, which can be advantageous if the motor needs to be specifically orientated or the position of the rotor known without using an external sensor, such as an encoder.

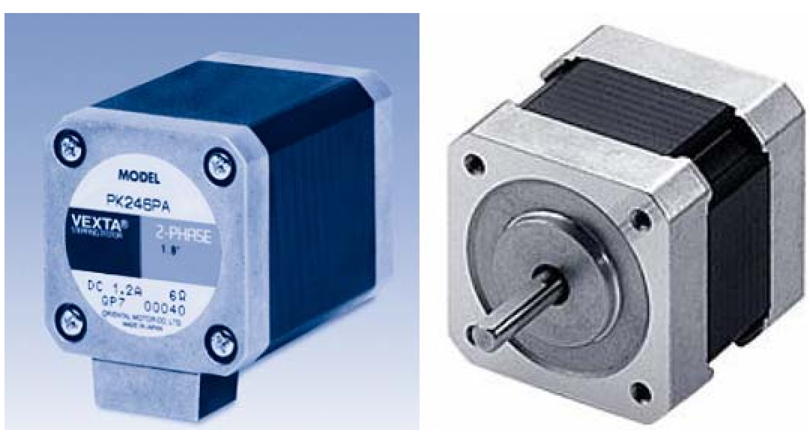

Figure 1: Stepper Motor Examples

A Stepper motor will generally be run in open-loop commutation, meaning no feedback from the motor is factored into the control. Depending on the design needs, stepper motors can also be used in closed-loop commutation. Stepper motors steps can be controlled to take discrete steps anywhere from one to hundreds of steps. However, with the discrete steps stepper motors are subject to higher vibrations than other motor types.

The stepper motors used in this circuit are 2-phase bipolar stepping motors with a minimum rated voltage of 10V. Both motors have six leads since they can also be used as unipolar stepping motors. Only four leads are used for bipolar operation, the two coils for each pole below are wired in series. Connections will be absent from coil taps 2 and 5.

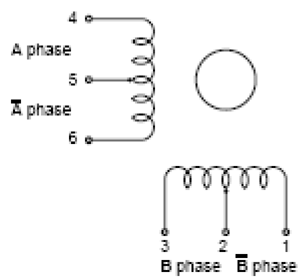

Figure 2: Typical Unipolar/Bipolar Stepping Motor Wiring

DC/DC Converter

The LM2576-5V is a 3.0 A at 5V DC to DC step down regulator. It can take a 7-40V DC unregulated input and convert it to 5V DC regulated output. The LM2576-5V is a Buck-Boost Converter built into an integrated circuit that needs only four external components. The IC has a built in 52 kHz oscillator and comparator for PWM switching, it also has a built in current limit circuit.

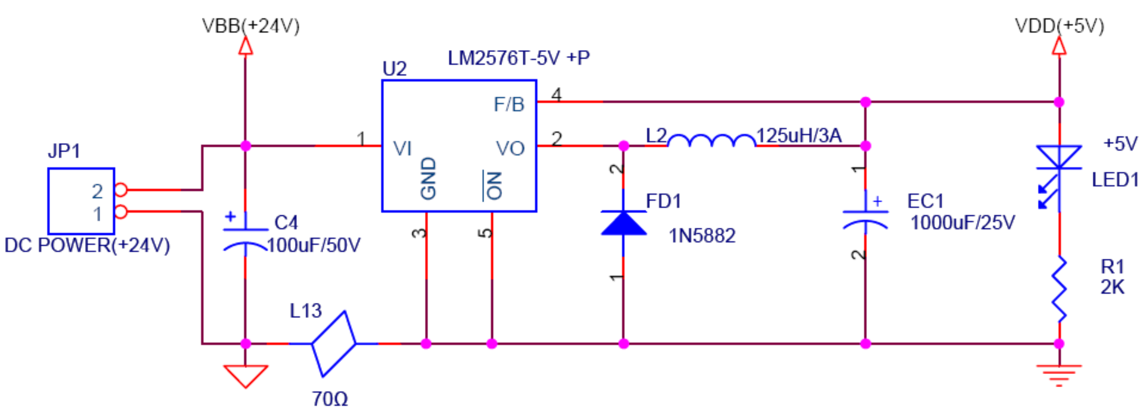

Figure 3: Implementation of LM2576-5V

In addition to the four external components needed for the IC, a ferrite bead is added to the circuit to isolate the analog ground from the digital ground for EMI protection and an LED circuit is added to indicate that power is on. The internal workings of which can be seen in Fig. 4.

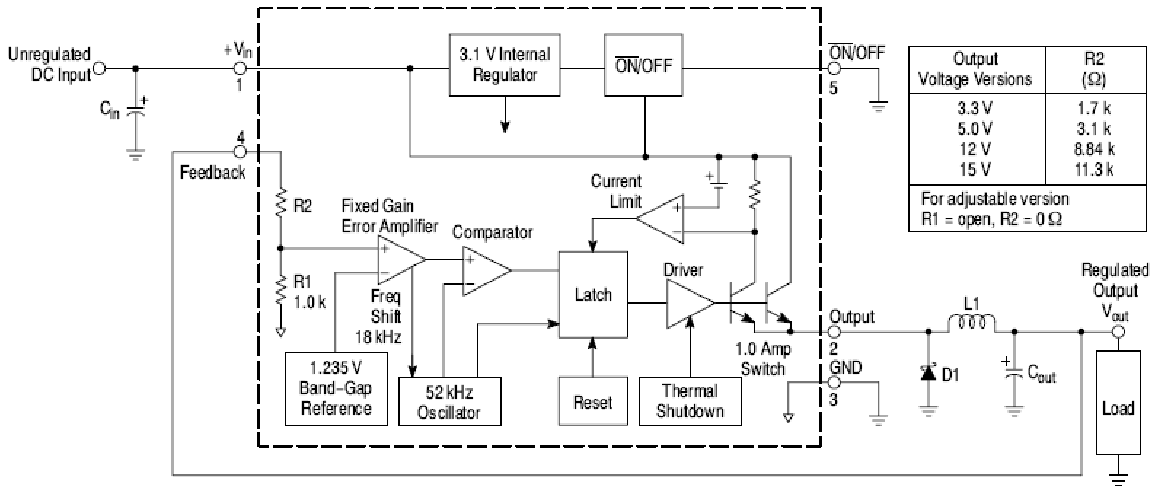

Figure 4: Internal Block Diagram of LM2576-5V

The input capacitor is not part of the switching circuit; it is there for protection from large input voltage transients. The protection helps maintain a steady voltage at the input of the IC, allowing for simpler implementation and a more stable output. A large capacitor with a low equivalent series resistance should be mounted close to the input pin and the ground pin. No calculations are necessary in determining a value for the input capacitor, however, the manufacturer of the IC recommends at minimum a 100 μF electrolytic capacitor rated at least 10 V greater than the maximum specified input voltage, in this case, 24 V.

The recommended diode is a 1N5822, different from what is specified in the drawing. The 1N5882 specified is rated for 1.8 mA at 68 V, nowhere near large enough to even handle the power of one of the ICs. The 1N5822 is rated for an average forward current of 3.0 A.

The input voltage specified is 24 V DC and in order to supply the full rated current, the inductor is selected from Fig. 5, 100 μH. The circuit is run in continuous conduction mode and the inductor can also be chosen accordingly by normal buck converter calculations, shown below, which confirm manufacturers recommendations.

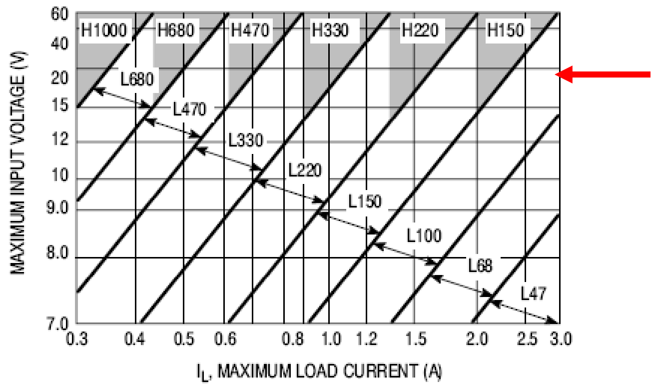

Figure 5: Inductor Selection

$$i_{Lon} = \frac{(V_{in} - V_o)T_{on}}{L} \qquad 3A = \frac{(V_{in} - V_o)T_{on} + (V_o - V_D)T_{off}}{2L}$$

$$i_{Loff} = \frac{(V_o - V_D)T_{off}}{L} \qquad L = \frac{(24V - 5V)4\mu s + (5V - 0V)15\mu s}{2(3A)}$$

$$i_{Lave} = \frac{i_{Lon} + i_{Loff}}{2} \qquad L > 25\mu H$$

The inductor selection also needs to take into account the peak current seen by the inductor. The peak current is given by:

$$I_{p(Max)} = I_{Load(Max)} + \frac{(V_{in} - V_{out})t_{on}}{2L} = 3 + \frac{(24V - 5V)4\mu s}{2 * 100\mu H} = 3.38A$$

$$V_{in} = 24V \qquad D = V_{out}/V_{in} = 0.208333$$

$$V_{out} = 5.0V$$

$$I_{out} = 3.0A \qquad t_{on} = D/f_s = 0.208333/52000kHz$$

$$f_s = 52000kHz$$

Taking into account the max current of the microprocessor, three stepper motor controllers, and likely overestimating the max current used by the remaining components, sizing the inductor at exactly 3.0 A is reasonable.

Qty.	Component	Max Current
1	Microprocessor	19 mA
3	Microstepping DMOS Driver	20 mA
n/a	Miscellaneous	0.75 A
	Total	0.9 A

Figure 6: Power Usage

$$I_{p(Max)} = 0.9A + \frac{(24V - 5V)4\mu s}{2 * 100\mu H} = 1.28A < 3.0A$$

The IC manufacturer suggests that the output capacitor should be between 680 and 2000 µF. A 1000 µF capacitor is used in both the typical schematic in the datasheet and in the design. Using standard calculations for an output capacitor for a ripple of one percent of the output voltage, the output capacitor should be greater than 240 µF.

$$\Delta V_{out} = \frac{I_{out} * D}{f_s * C} < 1\% * V_{out}$$

$$C > \frac{3.0A * 0.208333}{52kHz * 0.01 * 5.0V} = 240\mu F$$

Stepper Motor Controller

The motor controller is an Allegro A3977SED, not a A3997SED shown in the schematic (Fig. 8). The IC can control if the motor makes a half, quarter, eight, or whole rotation; the size of the step is controlled by the microstep select input pins, MS1 and MS2 (Fig. 7). The controller has seven digital inputs from the microprocessor for different functions, and two sets of outputs for each coil of the stepper motors.

MS1	MS2	Resolution
L	L	Full step (2 phase)
H	L	Half step
L	H	Quarter step
H	H	Eighth step

Figure 7: Step Size Selection

The stepper motor is controlled with two H-bridges internal to the controller. The input voltage to the H-bridge is the input voltage to the circuit, 24 V. Each H-bridge controls the current and the direction of current to one of the coils. The direction of the current through the coil controls the direction of rotation.

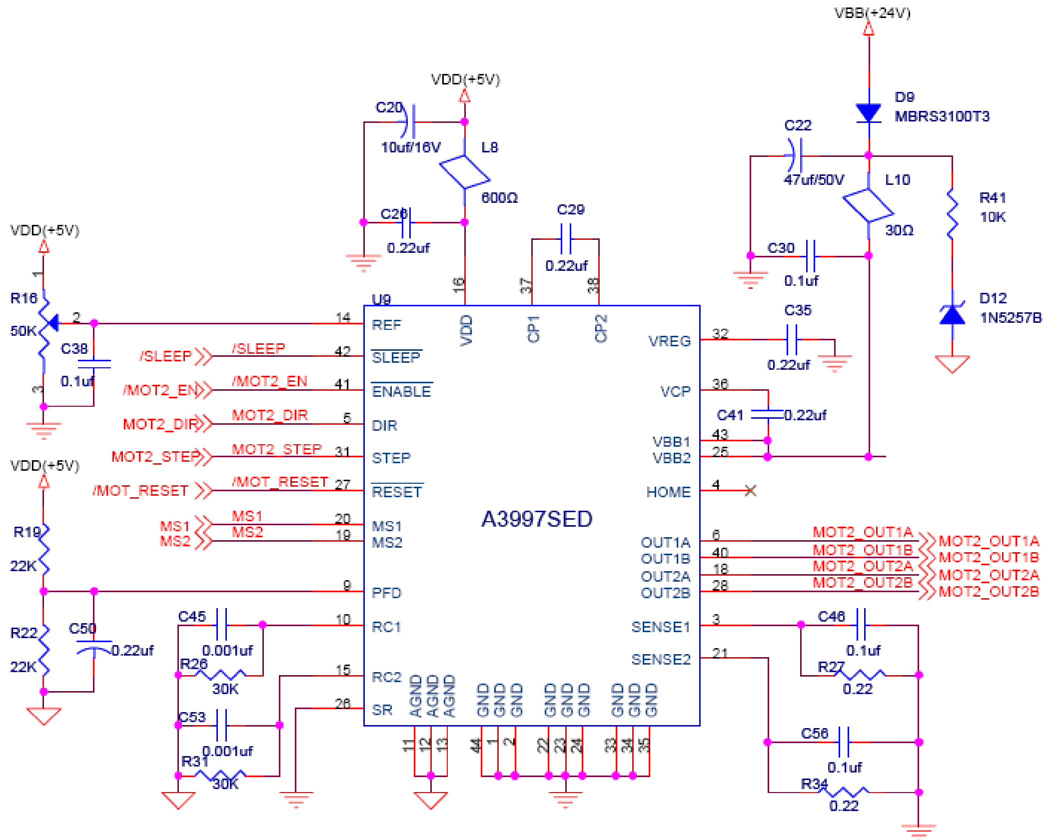

Figure 8: Implementation of A3977SED

The H-bridges works by turning on two of the DMOS devices at a time; for example, in the close-up of the H-bridge configuration seen in Fig. 9, the top left FET will be turned on, applying VBB1 to OUT1A, and the bottom right FET will be turned on simultaneously, allowing OUT1B to be connected to ground, completing the circuit path (Fig. 9). A positive voltage is now across the motor coils forcing in to turn in the positive relative direction. To reverse the motor, the top right and bottom left FETs are switched on to apply a negative voltage across the motor coils.

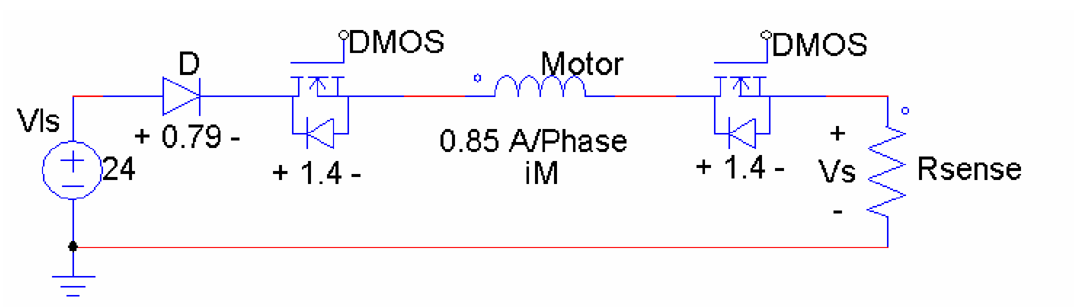

Figure 9: Motor Circuit Path One Phase

The current flowing through the motor is sensed by the voltage across an RC circuit between the motor and the ground. The sensing resistors need to have very small values as to not consume a lot of power and the capacitors are for decoupling. The sensing resistors also function as current limiters and are related to the maximum current by:

$$I_{TRIP(Max)} = \frac{V_{ref}}{8R_{Sense}}$$

The reference voltage is set by a voltage divider across a 50 kΩ potentiometer with a capacitor across the potentiometer wiper to ground to smooth out any voltage transients and further reduce the voltage ripple from the power supply. Assuming a reference voltage of 2.4 V and using the sensing resistor specified in the design, the current will be limited to 1.36 A for each stepper motor.

This current is negatively fed back to the PWM controller to control the current at that specific step location. The current to be fed via PWM switching to each of the H-bridges is a specific percentage of the full load current which is distinctive for each particular step in the rotation as can be seen in Fig. 15 in the appendix. Each H-bridge is 90º out of phase and the vector addition of the currents always add up to 100 percent of the max current limited by the sensing resistor and reference voltage.

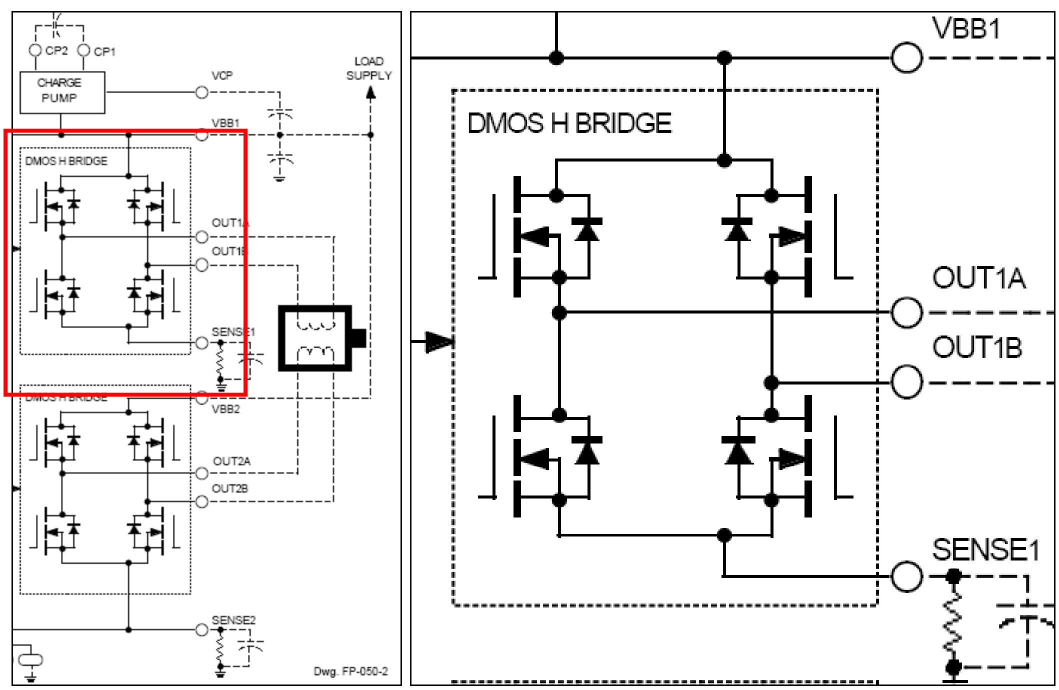

Figure 10: H-Bridge configuration Internal to A3977SED

The two extreme examples for this controller can be found in Fig. 14 in the appendix. The inputs RC1 and RC2 define the fixed off-time for the PWM switching; the external components related to the off-time are two more equal sets of RC circuits and are both related by:

$$t_{off} = RC$$

The manufacture recommends an off-time range of 5.6 μs to 0.15 ms. The off-time for each of the microstepping controllers in the design is 30 μs.

	R (kΩ)	C (pF)	toff
Min	12	470	5.6 μs
Max	100	1500	1.5 ms
Spec	30	1000	30 μs

Figure 11: PWM Fixed Off-Time

The charge pump capacitor is needed to fire the DMOS devices which have a higher gate voltage required for switching than the load voltage.

The power supply for the motor load is 24 V DC protected by a power diode capable of handling a forward current of 3.0 A. The 1N5257B zener diode has a breakdown voltage of 33 V and its intended application is as follows; if the supply voltage ever gets over 33 V, the voltage will be regulated to keep the load voltage under the absolute maximum voltage rating for the controller, 35 V. Two capacitors are in parallel with the load to smooth out any voltage transients from the supply and a ferrite bead is added to isolate the analog input voltage from the digital ground.

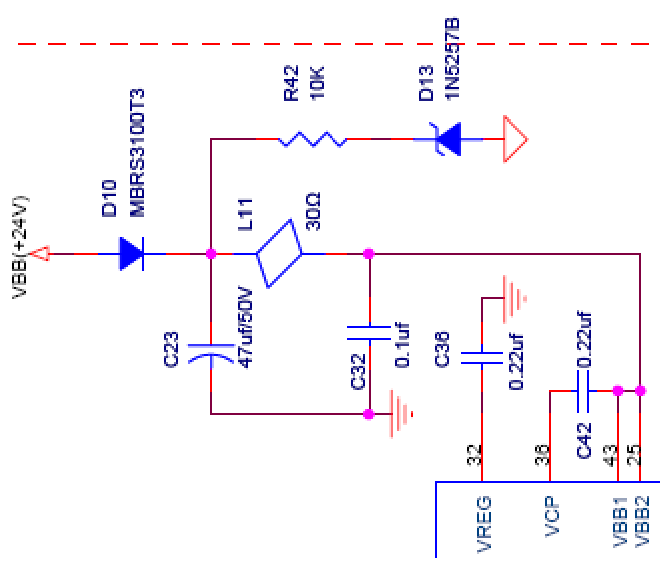

Figure 12: Regulation Circuit for Motor Supply Voltage

µController

The three microstepping controllers are controlled by ATmega 128; thirteen consolidated outputs are used to control the seven inputs on each of the A3977SEDs. Two of the consolidated outputs (MS1 and MS2) control the step size, as discussed previously, for all three controllers. The other two consolidated outputs going to the A3977SEDs are the sleep and reset, unless power consumption is a major design consideration, both are most likely programmed high to keep the microstepping controllers enabled. The outputs of the controllers, direction, and steps are all controlled individually by the microcontroller.

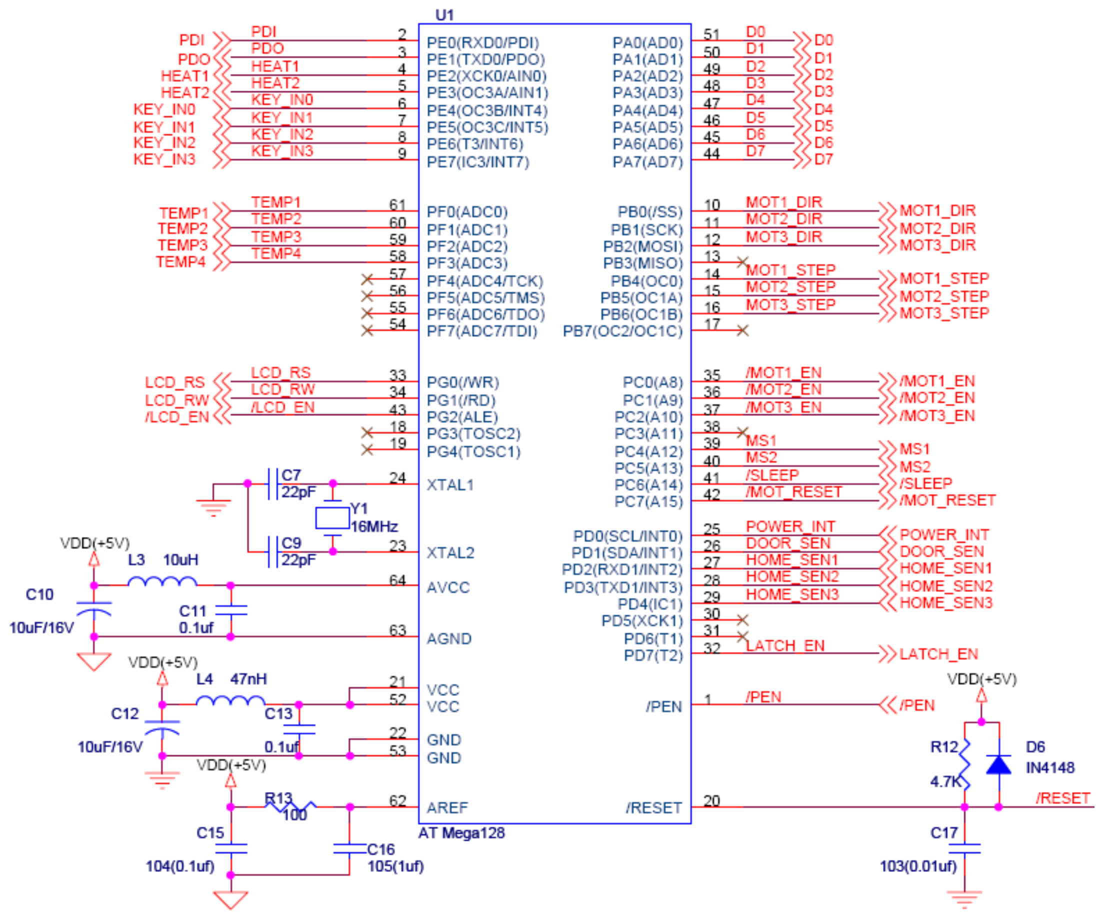

Figure 13: Implementation of AT Mega 128

When the motor has a large load or gets knocked out of place by an external entity, the microcontroller needs to zero out the stepper motor by moving to certain zero location or home. One way the zero location can be found is by hitting a barrier, then stepping a set amount of steps to the zero location or alternatively, by using a separate sensor outputting when the motor is at the zero location and stopping its rotation there. The home of each stepper motor in this particular design is sensed by an external sensor for each stepper motor.

The stepper motor controller controls the PWM control of the motor currents greatly simplifying the programming of the microprocessor. The speed of the stepper motors is controlled by the frequency of pulses sent by the MOTx_STEP outputs; to get the motors to a specific location, a programmed specific number of pulses needs to be sent at whatever frequency was specified.

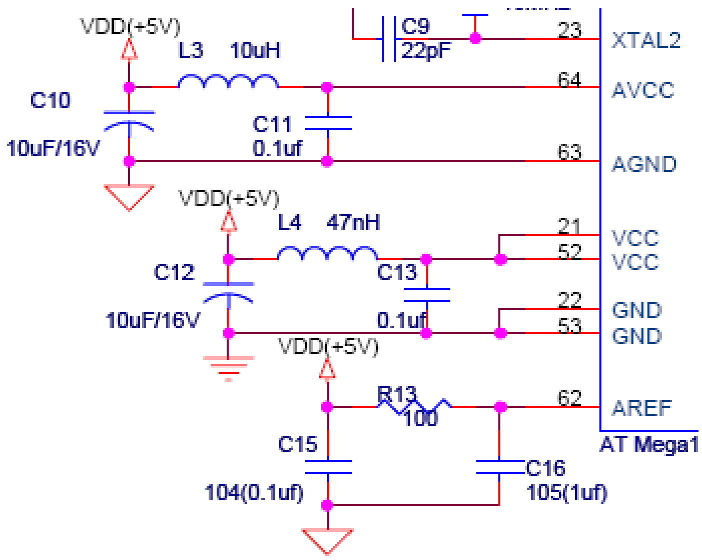

Figure 14: Input Voltage Filters

Large capacitors are put across the analog voltage, digital voltage, and analog reference voltage inputs for the microprocessor to protect against voltage sags and to reduce the voltage ripple. Low pass filters are also put on these input voltage sources to get rid of the AC harmonics from the DC/DC converter switching and in turn reduce the voltage ripple even further; the filter for the analog voltage input has a cutoff frequency of 100 MHz, 14.6 MHz for the digital voltage input, and 100 kHz for the analog reference.

Conclusion

Overall, the design appears solid; the main issue with the design appears to be the voltage regulation of the stepper motors. The 10 kΩ resistor will mask the true voltage from the zener diode. Minor issues are the two incorrect parts on the schematic; the 1N5882 diode as opposed to the 1N5822 and the A3997SED as opposed to the A3977SED.

If power conservation were an issue, each stepper motor controller should get its own sleep command to lower the power consumption when that particular stepper motor is not in operation. However, this would slow down the response time slightly as the stepper motor controllers need a 1 ms delay to wake up.

Appendix

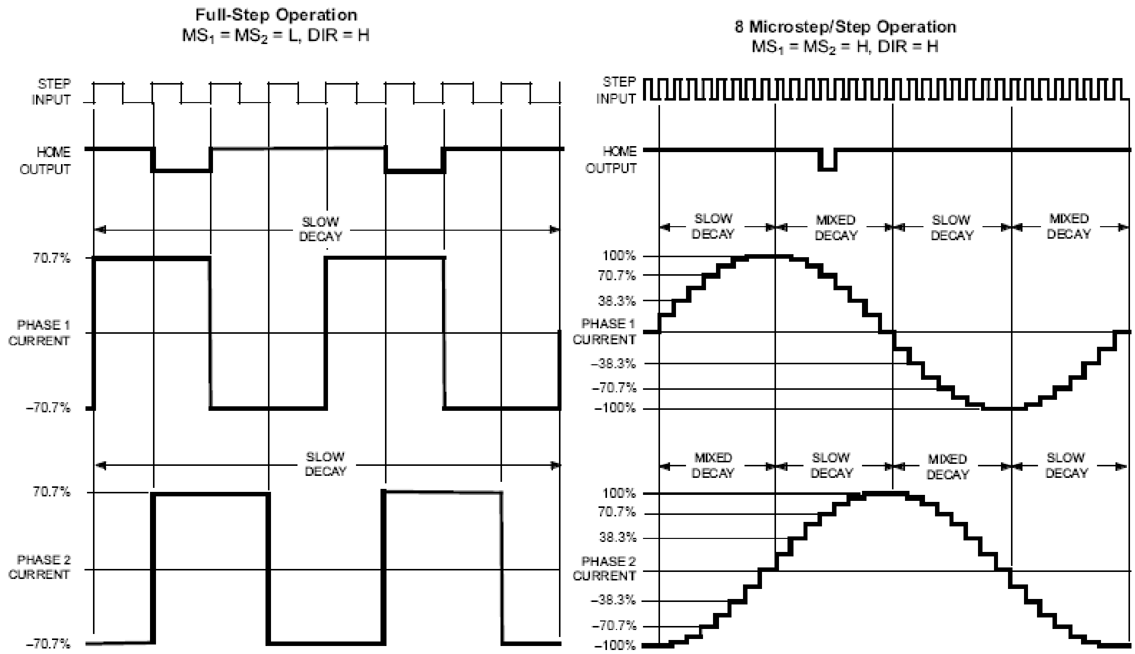

Figure 15: PWM Switching Currents for 1 Step Rotations and 8 Step Rotations

References

1. Atmel ATmega128 User Manual, 2467P–AVR–08/07
2. Semi LM2576 Datasheet, LM2576/D
3. Allegro 3977 Datasheet, 26184.22D
4. Io 1N5820 Thru 1N5822 Datasheet
5. Vexta PK Series Datasheet, 1K/2-03/JH
6. Oriental Motor PK243-01AA Datasheet