AN718

Brush-DC Servomotor Implementation using PIC17C756A

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INTRODUCTION

This application note demonstrates the use of a PIC17C756A microcontroller (MCU) in a brush-DC servomotor application. The PIC17CXXX family of microcontrollers makes an excellent choice for cost-effective embedded servomotor control applications. Some of the benefits of the PIC17CXXX MCU family include fast instruction cycle execution (up to 120 ns), an 8 x 8 hardware multiplier, and many useful hardware peripherals. The application hardware is shown in Figure 1.

FIGURE 1: DC SERVOMOTOR APPLICATION HARDWARE

SYSTEM OVERVIEW

A block diagram of the servomotor system is provided in Figure 2. The system is comprised of the following elements:

- PIC17C756A MCU
- RS-232 Interface
- Power Amplifier
- Brush-DC Motor & Rotary Encoder

The MCU is responsible for communications with the host system, measuring the motor position, calculating the compensation algorithm and motion profile, and producing the drive signal sent to the power amplifier.

An RS-232 interface is the primary means of communication with the MCU. One of the two available USARTs on the MCU is used for this purpose. The operation of the motor is controlled and monitored from a host system using ASCII commands.

One of the three available pulse-width modulation (PWM) modules on the MCU is used to generate the motor drive signal. The PWM frequency is 32.2 kHz at a device operating frequency of 33 MHz and the module provides 10 bits of resolution. The torque applied to the motor is determined by the PWM duty cycle. The PWM signal is connected to a 'H'-bridge power amplifier capable of delivering up to 3A to the DC motor.

A Pittman Inc. 9234 series motor is used in this design. The motor has a no-load speed of 6151 RPM at 24 volts input and a torque constant of 5.17 oz-in/A (without gearbox). The peak stall current is 8.11A. A 5.9:1 ratio gearbox is installed on the output shaft.

A Hewlett Packard HEDS-9140 rotary optical encoder is mounted on the rear of the motor with a 500 count-per-revolution (CPR) encoder wheel mounted on the shaft. The encoder provides two pulse outputs that are in phase quadrature and a third index output that can be used to align the motor shaft to a reference position.

To save space, a stackable printed circuit board (PCB) system was designed that allows two PCBs to be mounted on top of the motor (see Figure 1). The bottom PCB contains a 5V regulator, motor driver, encoder interface, and limit switch buffer circuitry. The upper PCB contains the PIC17C756A MCU, crystal, RS-232 interface, and reset button.

HARDWARE DESCRIPTION

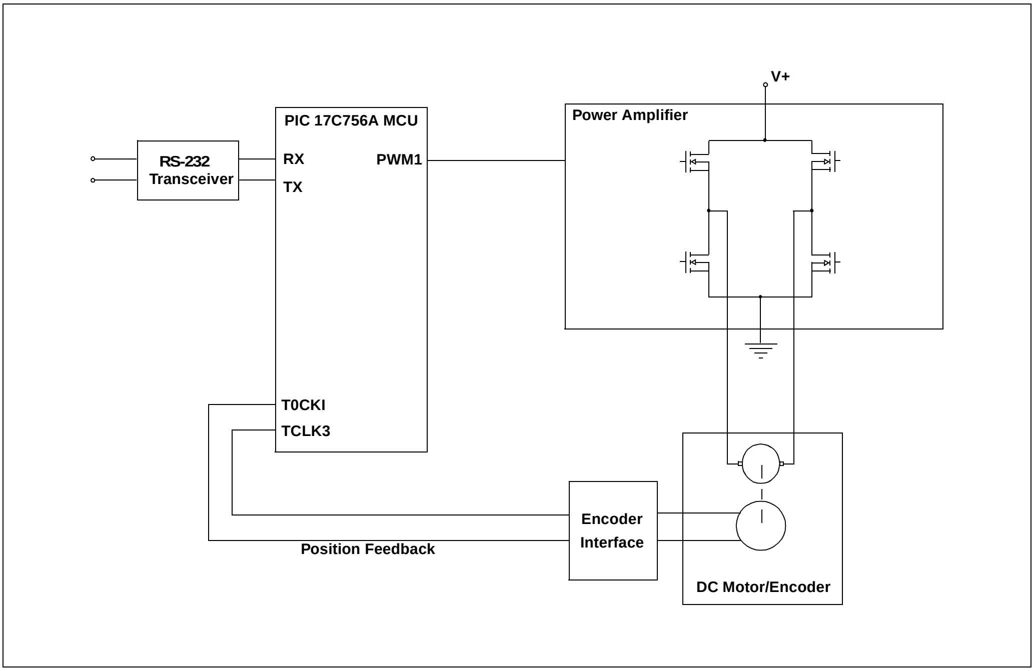
The design makes extensive use of the hardware peripherals available on the PIC17C756A. The peripherals used in this application are summarized in Table 1.

A complete schematic diagram for the application is given in Appendix A.

TABLE 1: PIC17C756A PERIPHERAL USAGE FOR DC SERVOMOTOR APPLICATION

Peripheral	Function
TMR0	Used as a counter to maintain the incremental up-count from the motor position encoder
TMR1	PWM1 time-base
TMR2	Servo update time-base
TMR3	Used as a counter to maintain the incremental down-count from the motor position encoder
PWM1	Generates drive signal for DC motor
USART1	Terminal communications
I/O	Encoder index signal, PWM amplifier enable, limit switch inputs

FIGURE 2: DC SERVOMOTOR BLOCK DIAGRAM



Motor Position Feedback

Referring to the schematic diagrams (Figure A-1 to Figure A-3), the outputs of the rotary encoder are connected to 2.7k pull-up resistors, filtered using RC networks, and buffered by Schmidt trigger inverters U5A - U5C. The outputs of the rotary encoder include two quadrature outputs and a third index output that is used to align the shaft of the motor to a known reference position. The conditioned index signal is connected to I/O pin RF0 of the MCU.

The conditioned quadrature outputs from the rotary encoder are connected to D flip-flops U6A and U6B. These D flip-flops decode the quadrature pulse train into up and down pulse outputs. A timing diagram indicating the operation of the decoder circuit is shown in Figure 3.

A simplified schematic diagram of the encoder interface is shown in Figure 4. The MCU accumulates the total distance traveled between servo updates based on the up and down pulse outputs from U6A and U6B. To accomplish this, Timer0 and Timer3 are configured as counters with external clock inputs. The output of D flip-flop U6A (up pulses) is connected to the Timer0 external clock input and the output of D flip-flop U6B (down pulses) is connected to the Timer3 external clock input. Each of these timer registers is 16 bits wide.

Three external logic inputs are provided at connector J4 on the motor driver PCB and are intended for mechanical limit switch sensing. These inputs could also be used to activate certain motor functions. The inputs are filtered and buffered by U5D – U5F similar to the encoder interface circuitry. The conditioned limit switch signals are connected to I/O pins RF1, RF2, and RF3 of the MCU.

PWM Amplifier

Integrated circuit U1 is an H-bridge driver that uses DMOS output devices and can deliver up to 3A output current at supply voltages up to 52V. The device has an internal charge pump for driving the high-side transistors and dead-time circuitry to prevent cross-conduction of the output devices. Each side of the bridge may be driven independently and the inputs are TTL compatible. An enable input and automatic thermal shutdown are also provided. A transient voltage suppressor is connected across the motor terminals to prevent voltage spikes generated by the motor inductance from damaging the bridge.

The PWM1 output from the MCU is buffered through inverters U3A, U3B, and U3D and connected to both sides of the H-bridge driver IC. One side of the bridge is driven with a inverted PWM signal. By driving the bridge in this manner, the motor may be turned in either direction depending on the PWM duty cycle. A 50% PWM duty cycle will produce zero motor torque. A 100% duty cycle will produce maximum motor torque in the forward direction, while a 0% duty cycle will produce maximum motor torque in the opposite direction.

An enable signal from I/O pin RF4 of the MCU is connected to the bridge driver through inverter U3C. This signal turns the output of the PWM amplifier on or off.

FIGURE 3: ENCODER TIMING

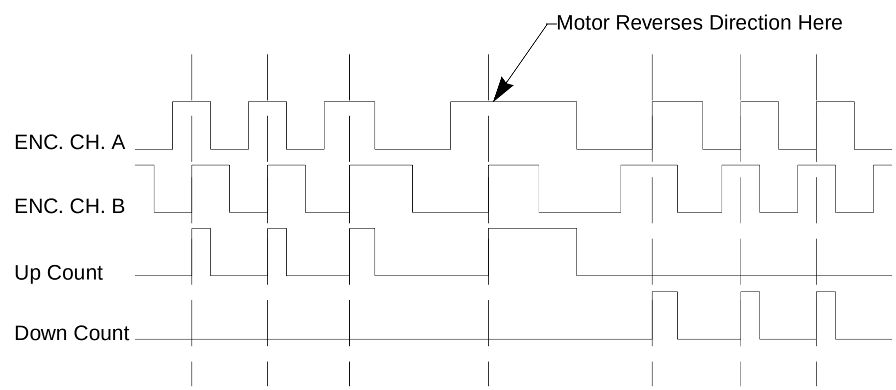
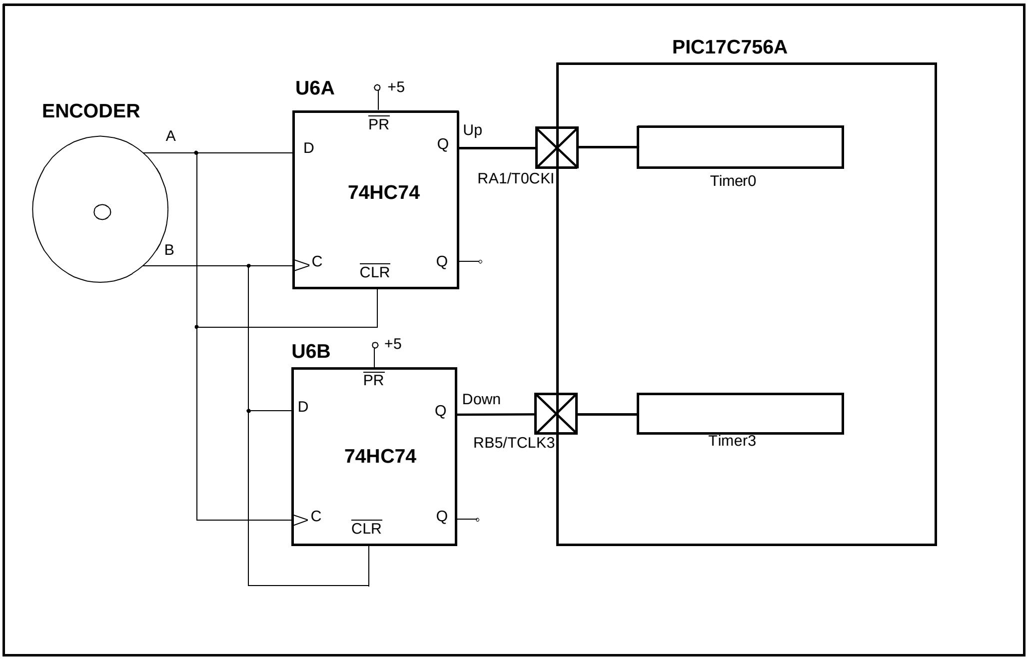


FIGURE 4: SIMPLIFIED ENCODER INTERFACE SCHEMATIC



Servo Update Timing

The servo update calculations are performed in an interrupt service routine and are synchronized with the output of PWM1. This is desirable because the duty cycle is updated at multiples of the PWM period. The PWM1 output is connected to the TCLK12/RB4 pin and is used as a clock source for Timer2. Timer2 has an associated period register, PR2. When the value of Timer2 is equal to the value loaded in PR2, Timer2 is reset to 0 and an interrupt is generated. By adjusting the value in PR2, the servo update frequency may be adjusted to any ratio of the PWM1 output. At a device operating frequency of 33 MHz, the frequency of PWM1 is 32.2 kHz. A 3.9 kHz servo update frequency will be achieved with the value in PR2 set to 8.

RS-232 Transceiver

The TX and RX pins of USART1 are connected to a Dallas Semiconductor DS275 RS-232 transceiver. The chip was selected for its small size and because it is line-powered. The chip uses power from the receive input to generate the correct RS-232 voltage levels while transmitting. To save space, RS-232 connections are made through a RJ-11 connector on the MCU PCB.

Power Supply

Voltage regulator VR1 provides 5 volts to the MCU, RS-232 driver, interface logic, and the rotary encoder. The system is designed to operate at any supply voltage between 10 volts and 24 volts. The supply voltage is connected directly to the PWM amplifier.

SOURCE CODE

The source code is written in the C programming language for ease of implementation and was compiled using the MPLAB-C17™ compiler. A complete source code listing for the application has been provided in Appendix B.

The source code performs four basic functions:

- RS-232 communication
- Motor position measurement
- Compensator algorithm calculation
- Motion profile calculation

All functions, except the RS-232 communications are performed in an interrupt service routine.

RS-232 Communications

The DC motor software allows control of the motor operating mode and parameter changes via a remote terminal with a RS-232 link operating at 19.2 kbaud. All RS-232 communication takes place in the main program loop. The USART1 reception interrupt flag (RC1IF) is polled to detect when a character has been received. Each received character is stored in a buffer, echoed to the USART, and the buffer index is incremented. This continues until the buffer is full or a <CR> is received. After a <CR> is received, the buffer contents are checked for numerical or command data and a 'READY>' prompt is sent to the terminal. If the command is not recognized, an error message is sent out.

Servo Updates

The servo calculations are performed each time a Timer2 interrupt occurs. A flowchart of the servo interrupt service routine (ISR) is shown in Figure 5.

32-bit Operations

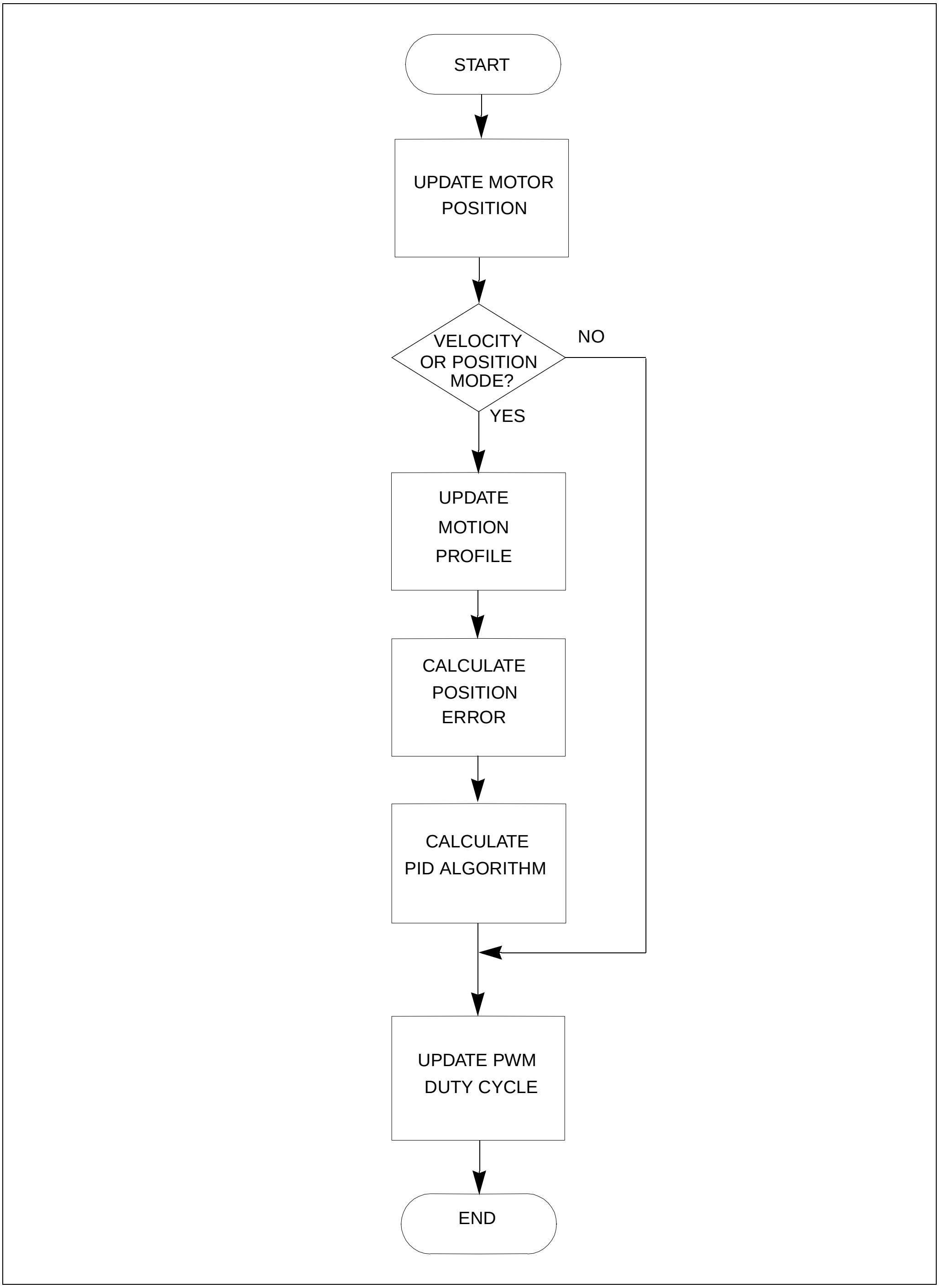
This application makes extensive use of 32-bit values. Since MPLAB-C17 does not provide direct support for 32-bit variable types, the 32-bit variables used in the program are declared as unions. The use of a union in the C programming language allows multiple variable types to share the same data space. A union with the name of 'LONG' has been declared in the source code. The union LONG consists of an array of four characters and an array of two integers. Therefore, any variables that are declared with this data type may be manipulated as four bytes or two integers. Additionally, the contents of the entire union may be copied to another location by simply assigning it to another union of the same type.

Position Updates

During each servo update period, the function `UpdatePosition()` is called. The count values in Timer0 and Timer3 are used to find the total motor distance traveled during the previous servo update period. The counters are never cleared to avoid the possibility of losing count information. Instead, the values of the Timer0 and Timer3 registers saved during the previous sample period are subtracted from the present values using two's-complement signed arithmetic. This calculation provides the total number of up and down pulses accumulated during the servo update period. The use of two's complement arithmetic accounts for a timer overflow that may have occurred since the last read. The down pulse count is then subtracted from the up pulse count, which provides a signed result indicating the total distance (and direction) traveled during the sample period. This value also represents the measured velocity of the motor in encoder counts per servo update period and is stored in the variable `mvelocity`.

The measured position of the motor is stored in the union `mposition`. The upper 24 bits of `mposition` holds the position of the motor in encoder counts. The lower eight bits of `mposition` represent fractional encoder counts. The value of `mvelocity` is added to `mposition` at each servo update period to find the new position of the motor. With 24 bits, the absolute position of the motor may be tracked through 33,554 shaft revolutions using a 500 CPR encoder. The size of `mposition` can be increased as necessary to track greater distances.

FIGURE 5: SERVO ISR FLOWCHART



The theoretical maximum encoder bit rate is determined by the number of bits in the counter registers and the servo update rate. If the counter should overflow between servo update periods, motor position information will be lost. A 16-bit counter register, for example, would provide $2^{16} - 1$ counts before an overflow occurred. Since two's complement arithmetic is used, the number of encoder counts during a given sample period must be limited to $2^{15} - 1$, or 32767. The maximum encoder rate is determined by multiplying the servo sampling frequency by the maximum encoder counts per sample. For this design, the servo update frequency is 3.9 kHz, which gives a theoretical maximum encoder rate of 128 MHz. In practice, the encoder rate is limited by the external clock timing specifications for Timer0 and Timer3. The minimum external clock period for Timer0 and Timer3 is T_{CY} + 40ns. Therefore, the maximum encoder rate is 6.2 MHz for a device operating frequency of 33 MHz.

PID Algorithm

The MCU must calculate and provide the correct motor drive signal based on the received motion commands and position/velocity feedback data. A compensation algorithm is used to ensure that the feedback loop is stabilized. Many types of algorithms may be used including various implementations of digital filters, fuzzy-logic, and the PID (proportional, integral, derivative) algorithm. A PID algorithm is used in this application since it is widely used in industrial applications and is easy to implement.

Figure 6 shows a flowchart indicating the function of the PID algorithm as it is implemented here. During each iteration of the servo loop, a position error is calculated and is used as the input to the algorithm. To control the operation of the PID algorithm, each of the three terms has a gain constant that can be adjusted in real-time by the user. Each term of the PID algorithm is calculated using a 16 bit x 16 bit signed multiplication algorithm with the PID gain constants `kp`, `ki`, and `kd` defined as 16-bit signed integers.

The union `position` holds the commanded motor position. The value of `mposition`, the measured motor position, is subtracted from `position` to find the present error in encoder counts. The least significant eight bits of these variables represent fractional encoder counts and are not used in the PID algorithm calculations. The `sub32()` function is used to subtract the values. The values to be subtracted are placed in `aarg` and `barg`. The result of the subtraction is available in `aarg` after the function has been called. The error calculation result in `aarg` is truncated to a signed 16-bit integer and stored in `u0`.

The multiplication routine is implemented as inline assembly instructions in the C source code. The algorithm executes in 36 cycles and takes advantage of the 8 x 8 hardware multiplier on the MCU. To perform the multiplication, the signed 16-bit integers to be multiplied are loaded into the `multplr` and `multcnd` variables and the function `mult()` is called. The 32-bit multiplication result is available in the union `aarg`. The `add32()` function is used to add the 32-bit terms of the PID algorithm.

The proportional term of the PID algorithm provides an output that is a function of the immediate position error, `u0`.

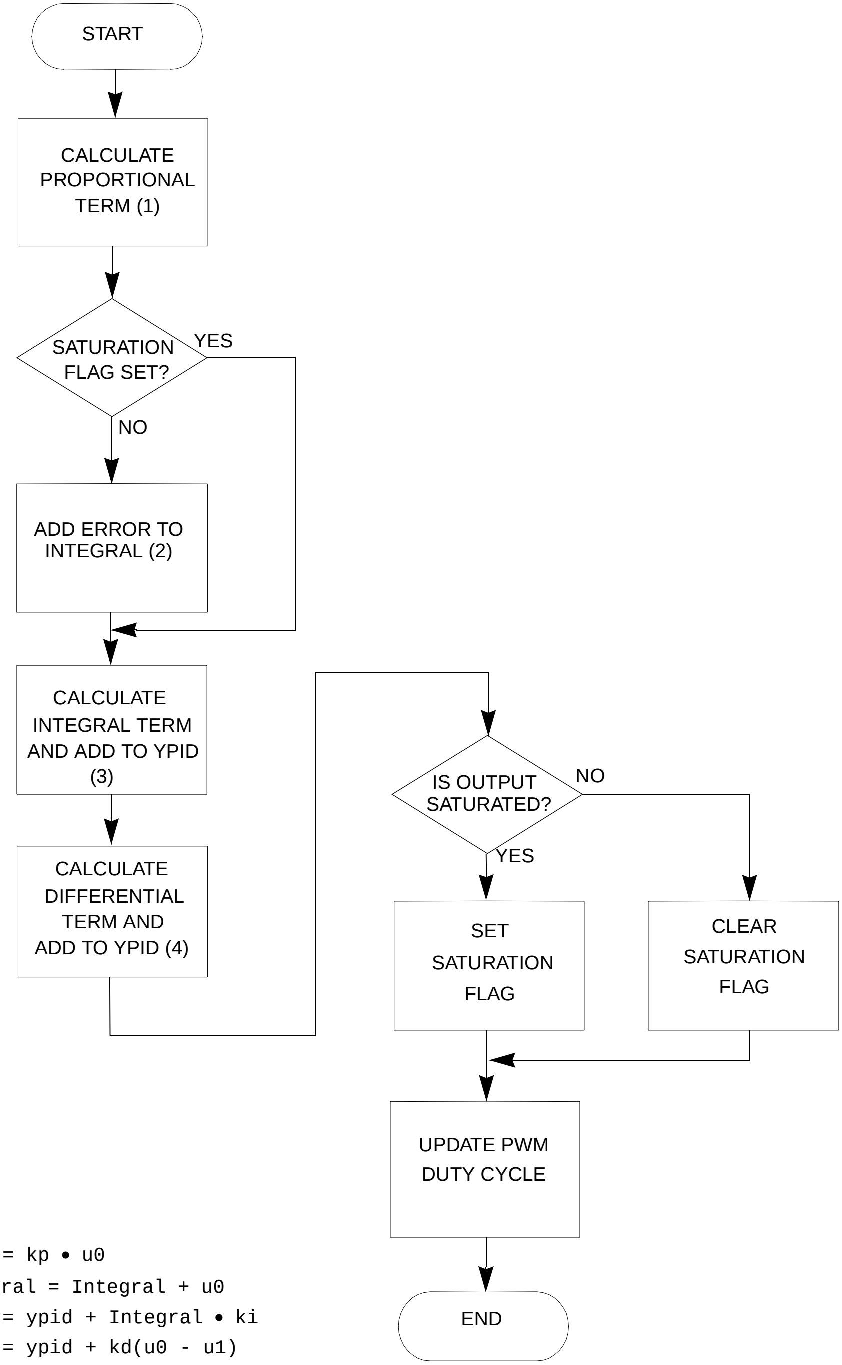
The integral term of the PID algorithm accumulates successive position errors calculated during each servo loop iteration and improves the low frequency open-loop gain of the servo system. The effect of the integral term is to reduce small steady-state position errors.

If the `stat.saturated` bit is set because the PWM output during the previous servo update period was saturated, the current position error is not be added to the integral value. This prevents a condition known as 'integrator-windup' that occurs when the integral term continues to accumulate error when the output is saturated. When the output is no longer saturated, the integral term 'unwinds' and causes abrupt motion as the accumulated error is reduced.

The differential term of the PID algorithm is a function of the difference in error between the current servo update period and the previous one. The integral term improves the high frequency open-loop response of the servo system.

After the three terms of the PID algorithm are summed, the 32-bit result stored in `ypid` is saturated to 24 bits. The 16-bit signed integer `ypwm` is used to set the PWM duty cycle. The upper 16 bits of `ypid` are used to set the duty cycle, which effectively divides the output of the PID algorithm by 256. The range of the duty cycle is restricted so that the PWM duty cycle cannot be less than 1% or greater than 99%. This ensures that Timer2 will always receive a valid clock input for the servo update timing interrupt. If beyond the limits, `ypwm` is set to the maximum allowable positive or negative value and `stat.saturated` is set to '1'. An offset value of 512 must be added to `ypwm` before it is written to the PWM duty cycle registers. (For 10-bit PWM resolution, a value of '0' written to the duty cycle registers provides a 0% duty cycle and a value of 1023 provides a 100% duty cycle.)

FIGURE 6: PID ALGORITHM FLOWCHART



(1) `ypid = kp • u0`
(2) `Integral = Integral + u0`
(3) `ypid = ypid + Integral • ki`
(4) `ypid = ypid + kd(u0 - u1)`

Motion Profile

For optimum motion control, a method must be implemented that will control the motor acceleration and deceleration. Motion will be abrupt without the profile, causing excessive wear on the mechanical components and degrading the performance of the compensation algorithm.

For this application, a simple motion profile that generates trapezoidal (or triangular) moves has been implemented. The profile characteristics are adjusted by specifying a 16-bit velocity limit, `vlim`, and a 16-bit acceleration value, `accel`. The motion profile is used in Velocity Mode and Position Mode. If the motor is operating in one of these modes, the function `UpdateTrajectory()` is called each time `ServoISR()` is executed.

A specific motor velocity is established by adding an offset value to the commanded position at each servo update period. The 32-bit variable `velact` is used in the profile to hold the present commanded velocity of the motor. The lower 24 bits of `velact` and the least significant 8 bits of `position`, the commanded motor position, represent fractional encoder counts. The purpose of these additional bits is to increase the range of velocities that may be achieved. To achieve a particular motor velocity, the upper 16 bits of `velact` are added to `position` during each step of the profile. This allows the commanded motor velocity to vary between 1/256 counts/T_S and 127 counts/T_S. The actual velocity range of the motor is dependent on the servo update rate and the resolution of the encoder. With a 3.9 kHz servo update rate and a 500 CPR encoder, the range of commanded motor velocities is from 1.8 RPM to 59,436 RPM.

Motor acceleration/deceleration is accomplished in a manner similar to the motor velocity. The value of `accel` is added to or subtracted from `velact` at each servo update period.

A flowchart for the operation of the motion profile in Velocity Mode is shown in Figure 7. In Velocity Mode, data entered at the prompt is stored in the commanded velocity variable, `velcom`. After `velcom` is updated, the motor begins to accelerate or decelerate to the new commanded velocity. Acceleration continues until `velact` is equal to `velcom` or the velocity limit, `vlim`, has been exceeded. The value of `velact` is added to the commanded motor position, `position`. The motor will continue to run at the commanded velocity or the velocity limit until further velocity data is received. If the output is saturated (`stat.saturated = ‘1’`) during a particular servo update period, the commanded position is not changed.

A flowchart for the operation of the motion profile in Position Mode is shown in Figure 8. In Position Mode, a 16-bit relative movement distance is entered as encoder counts divided by 256. The total movement distance is divided by 2 and placed in `phase1dist`. A second variable, `flatcount`, is set to zero. The direction of the move is determined and stored in the `stat.neg_move` flag. The final move destination is calculated based on the present measured position and is stored in `fposition`. Finally, the `stat.move_in_progress` flag is set. Further position commands are ignored until the move has completed and this flag is cleared.

The motor begins to accelerate and the value of `velact` is subtracted from `phase1dist` at each servo update period to keep track of the distance traveled in the first half of the move. The value of `velact` is added or subtracted from the commanded motor position, `position`, depending on the state of the `stat.neg_move` flag. The motor stops accelerating when `velact` is greater than `vlim`. After the velocity limit has been reached, `flatcount` is incremented at each servo update period to keep track of the time spent in the flat portion of the move.

The first half of the move is completed when `phase1dist` becomes negative. At this time, the `stat.phase` flag is set to ‘1’. The variable `flatcount` is then decremented at each servo period. When `flatcount = 0`, the motor begins to decelerate. The move is complete when `velact = 0.` The previously calculated destination in `fposition` is written to the commanded motor position and the `stat.move_in_progress` flag is cleared at this time.

FIGURE 7: MOTION PROFILE FLOWCHART – VELOCITY MODE

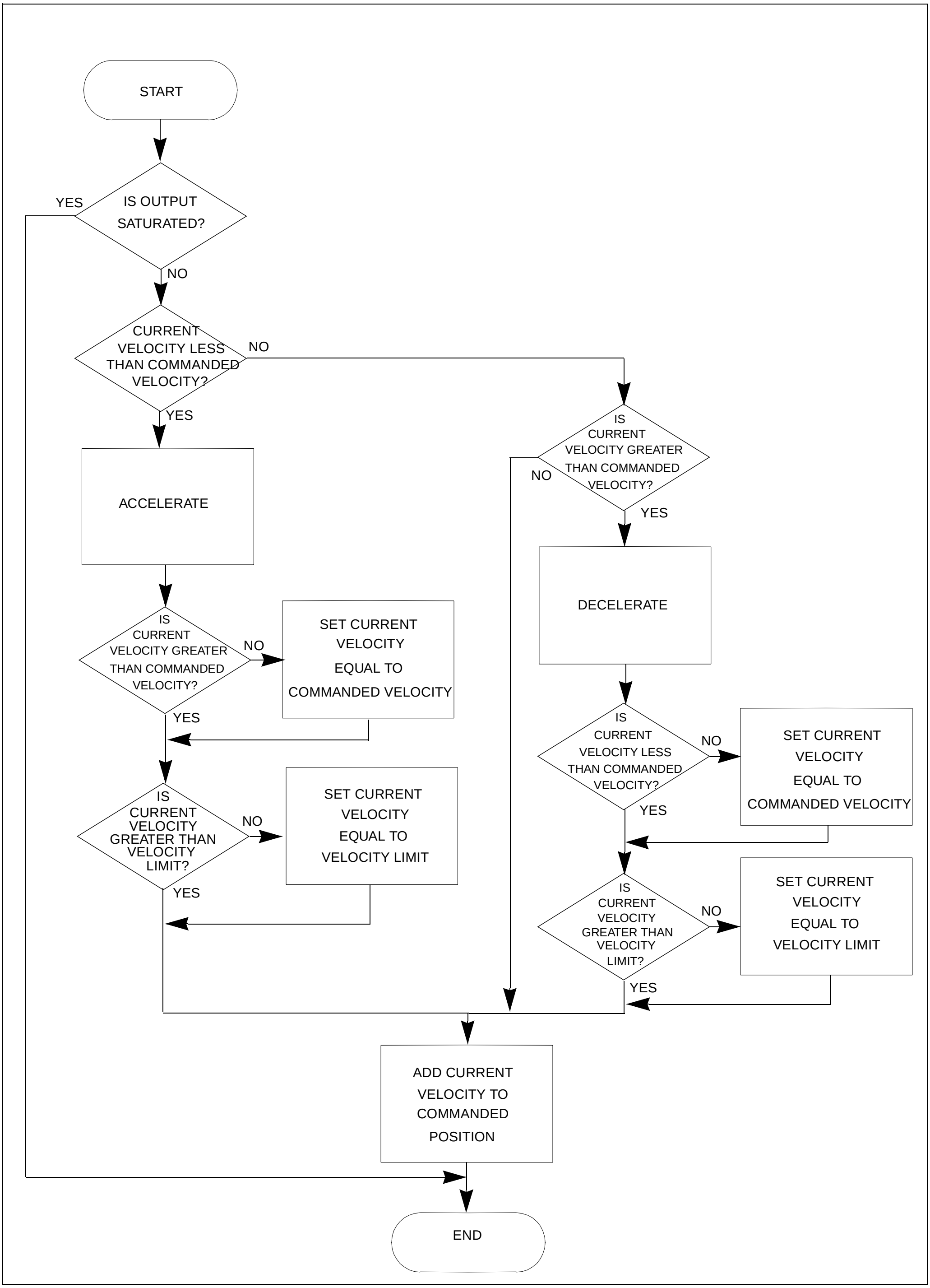
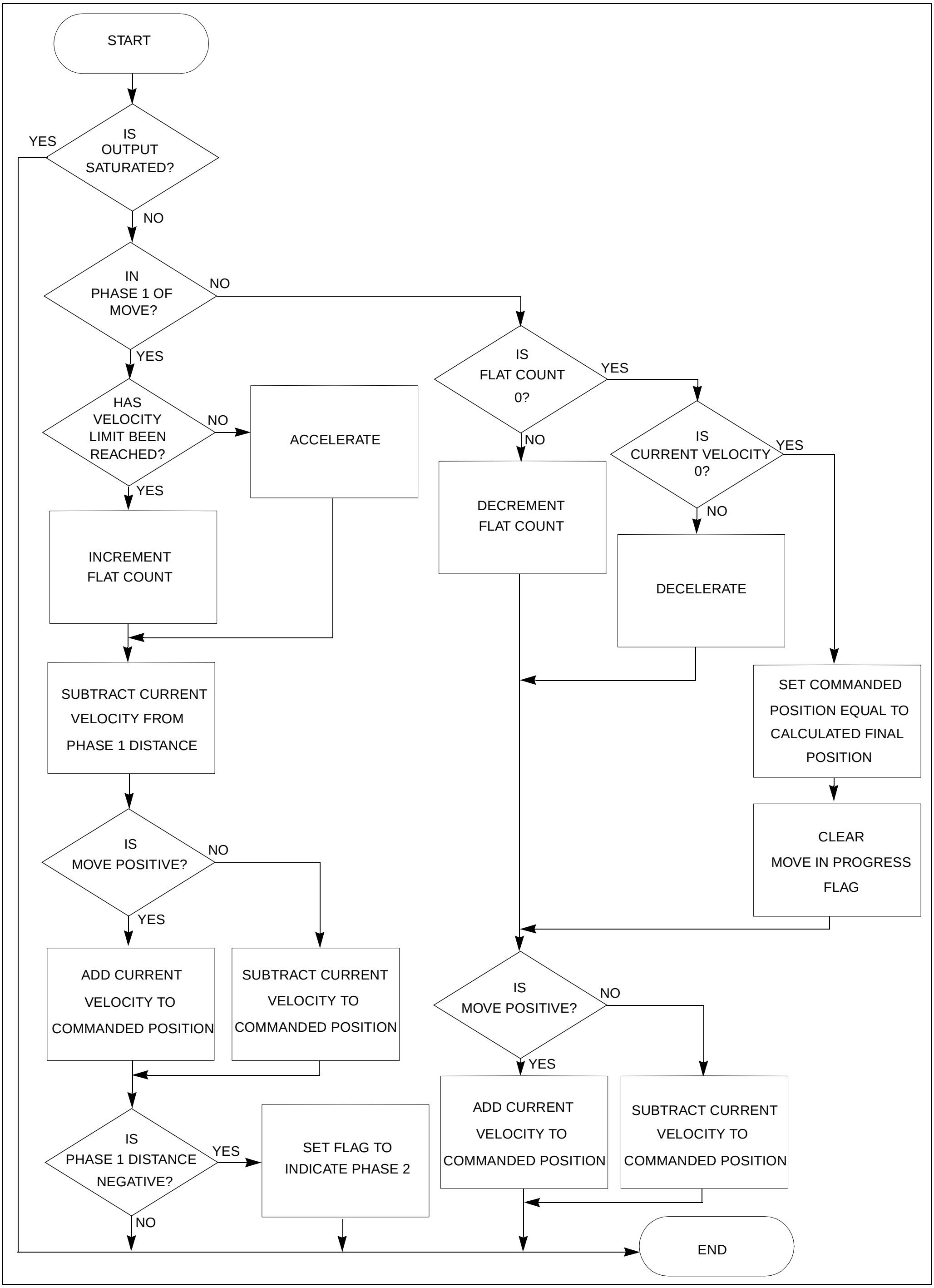


FIGURE 8: MOTION PROFILE FLOWCHART – POSITION MODE



USER INTERFACE

When power is first applied to the motor, the user will see a ‘READY>’ prompt appear on the terminal. At this time, the DC motor is ready to receive commands. A summary of all the commands is given in Table 2.

The software that controls the DC motor allows three basic modes of operation that are selectable from the remote terminal. These modes include Manual Mode, Velocity Mode, and Position Mode.

The default mode for the motor at power-up is Manual Mode. No position feedback is used in Manual Mode. The data entered at the prompt directly controls the PWM duty cycle delivered to the motor.

In Velocity Mode, the entry data specifies the signed motor velocity, which is given as encoder counts per sample period multiplied by 256. When new velocity data has been entered, the motor will accelerate or decelerate to the new velocity at a rate specified by the acceleration value. The motor will not accelerate if the velocity limit has been reached.

In Position Mode, the entry data specifies a signed 16-bit relative move distance. The movement distance, entered at the prompt, is given as encoder counts divided by 256. When a move distance is specified, a motion status flag is set and any additional move data are ignored until the current move is complete.

The profile of the move will be trapezoidal or triangular depending on the total move distance, the velocity limit, and the acceleration value. For a trapezoidal move, the motor will accelerate to the velocity limit and remain at that velocity until it is time for the motor to decelerate. If half of the move distance has been traveled before the motor reaches the velocity limit, the motor will begin to decelerate and the move will be triangular.

The motor operating parameters are displayed using the ‘R’ command. Any of the parameters may be modified by first entering the command to change the parameter, followed by a carriage return (<CR>). The parameter is then modified by entering the new value followed by a <CR>. The user can then verify that the parameter was changed by using the ‘R’ command again.

SUMMARY

The use of the PIC17C756A MCU in a DC servomotor application has many features that allow a cost-effective implementation with few external components. These include (2) 16-bit counters for position measurement, hardware PWM modules, and a hardware multiplier for high computational throughput.

`ServoISR()`, as written for this application, executes in 780 instruction cycles. For a servo update rate of 3.9kHz and a MCU clock frequency of 33 MHz, only 37% of the total MCU processing time is consumed. This provides additional time for performing unrelated tasks, computing more complicated compensator algorithms, or increasing the servo update rate.

TABLE 2: DC SERVO MOTOR COMMAND SUMMARY

Command	Data Range	Description
M <CR>	$-500 \le data \le 500$	Changes to the manual mode of operation. All subsequent data input is written directly to the PWM output.
V <CR>	$-32768 \le data \le 32767$	Changes to velocity mode. All subsequent data input is velocity in encoder counts per sample period multiplied by 256.
P <CR>	$-32768 \le data \le 32767$	Changes to position mode. All subsequent data input is a relative position move in encoder counts multiplied by 256.
W <CR>		Enables/disables PWM drive to the motor; the default is disabled.
R <CR>		Displays current K_P, K_I, K_D, velocity limit, and acceleration limit.
L <CR>		Displays the present motor position in hexadecimal format.
KP <CR> data <CR>	$-32768 \le data \le 32767$	Changes the proportional gain factor of the PID algorithm. The command is followed by the data value.
KI <CR> data <CR>	$-32768 \le data \le 32767$	Changes the integral gain factor of the PID algorithm. The command is followed by the data value.
KD <CR> data <CR>	$-32768 \le data \le 32767$	Changes the differential gain factor of the PID algorithm. The command is followed by the data value.
KV <CR> data <CR>	$0 \le data \le 65535$	Changes the velocity limit of the trajectory profile. The data value is encoder counts per sample period multiplied by 256. The command is followed by the data value.
KA <CR> data <CR>	$0 \le data \le 65535$	Changes the acceleration value for the trajectory profile. The command is followed by the data value.
KS <CR> data <CR>		Changes the servo update rate. The data value is written to the period register for Timer2. The servo update rate will be the PWM frequency divided by the value entered here.

APPENDIX A: SCHEMATICS

FIGURE A-1: SCHEMATIC 1

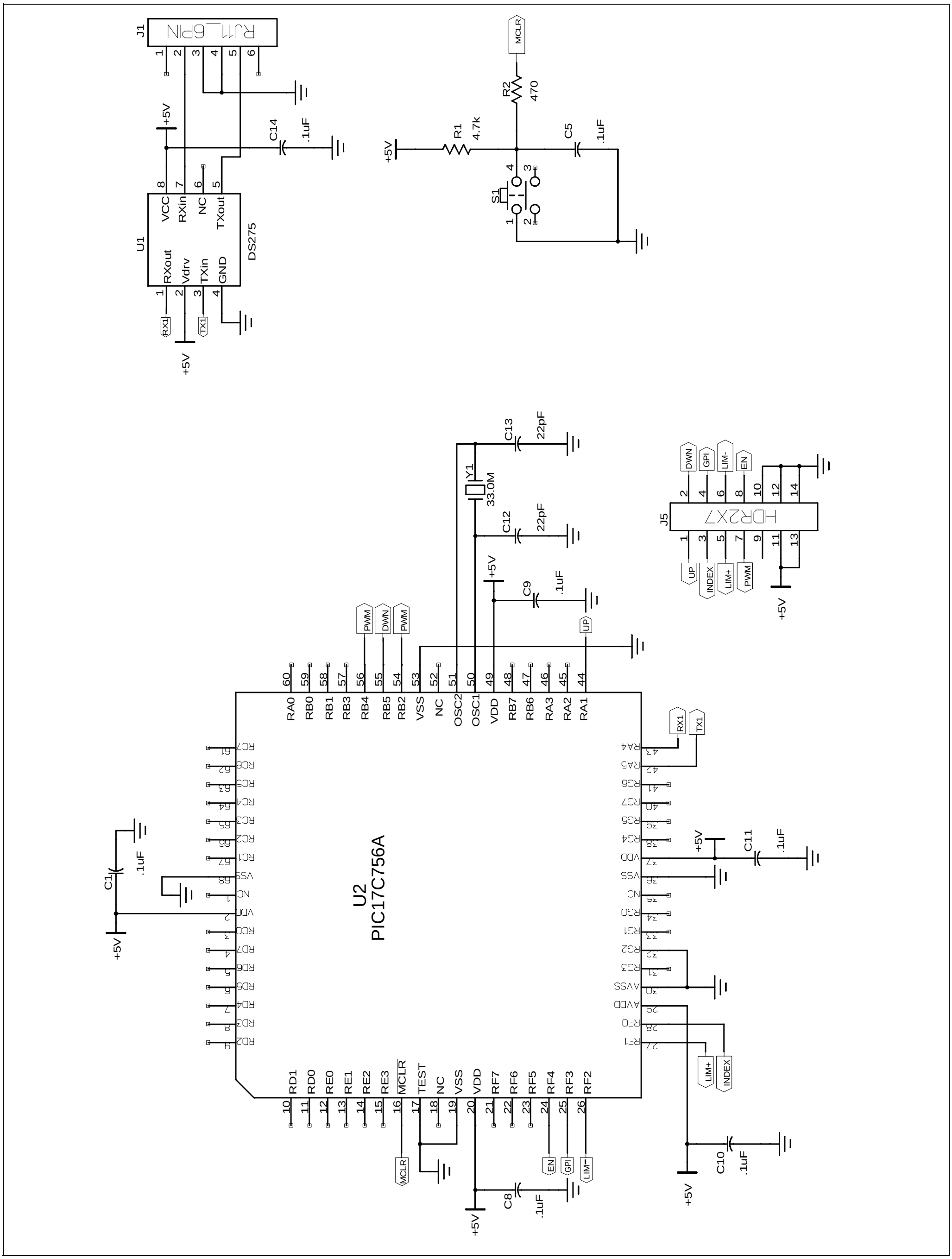


FIGURE A-2: SCHEMATIC 2

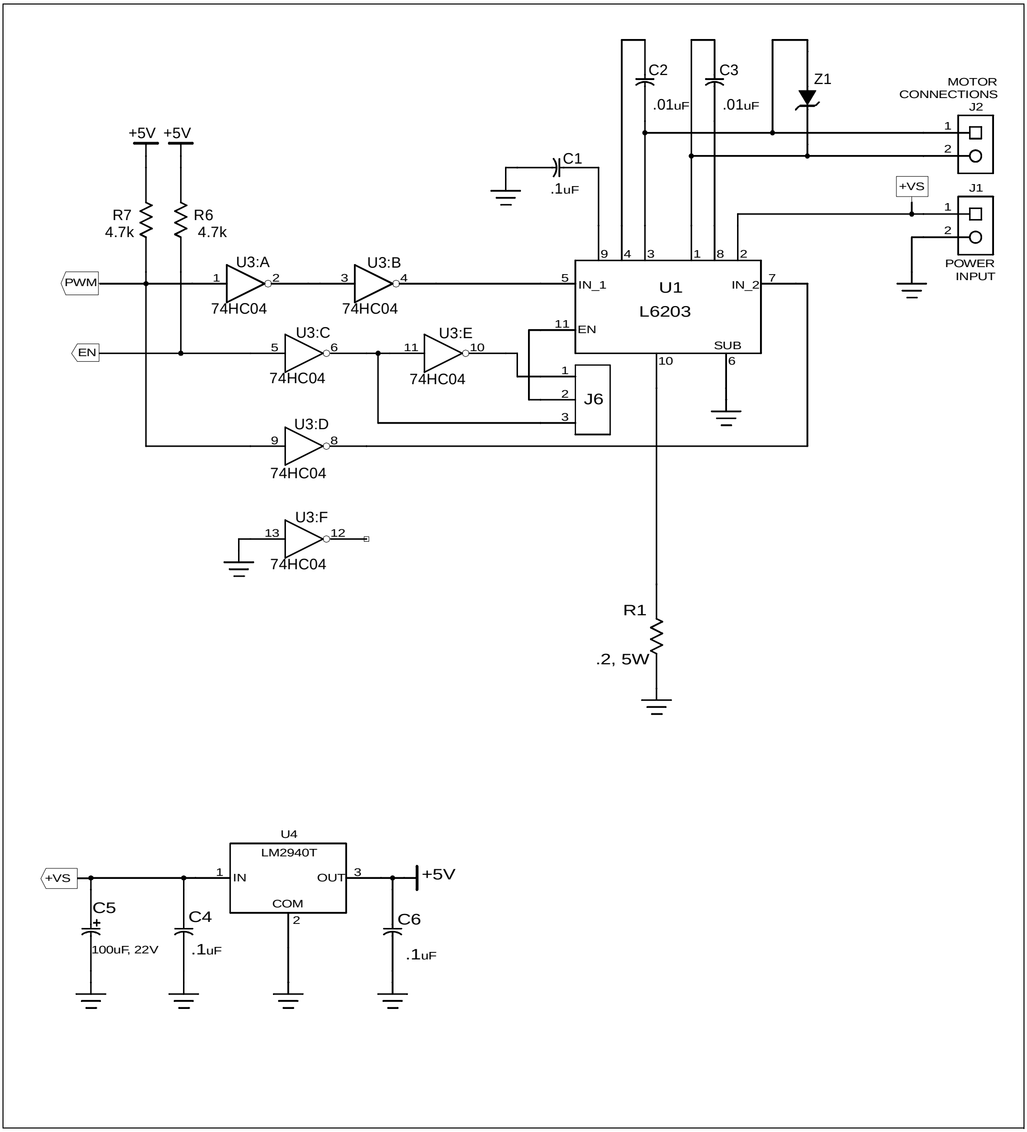
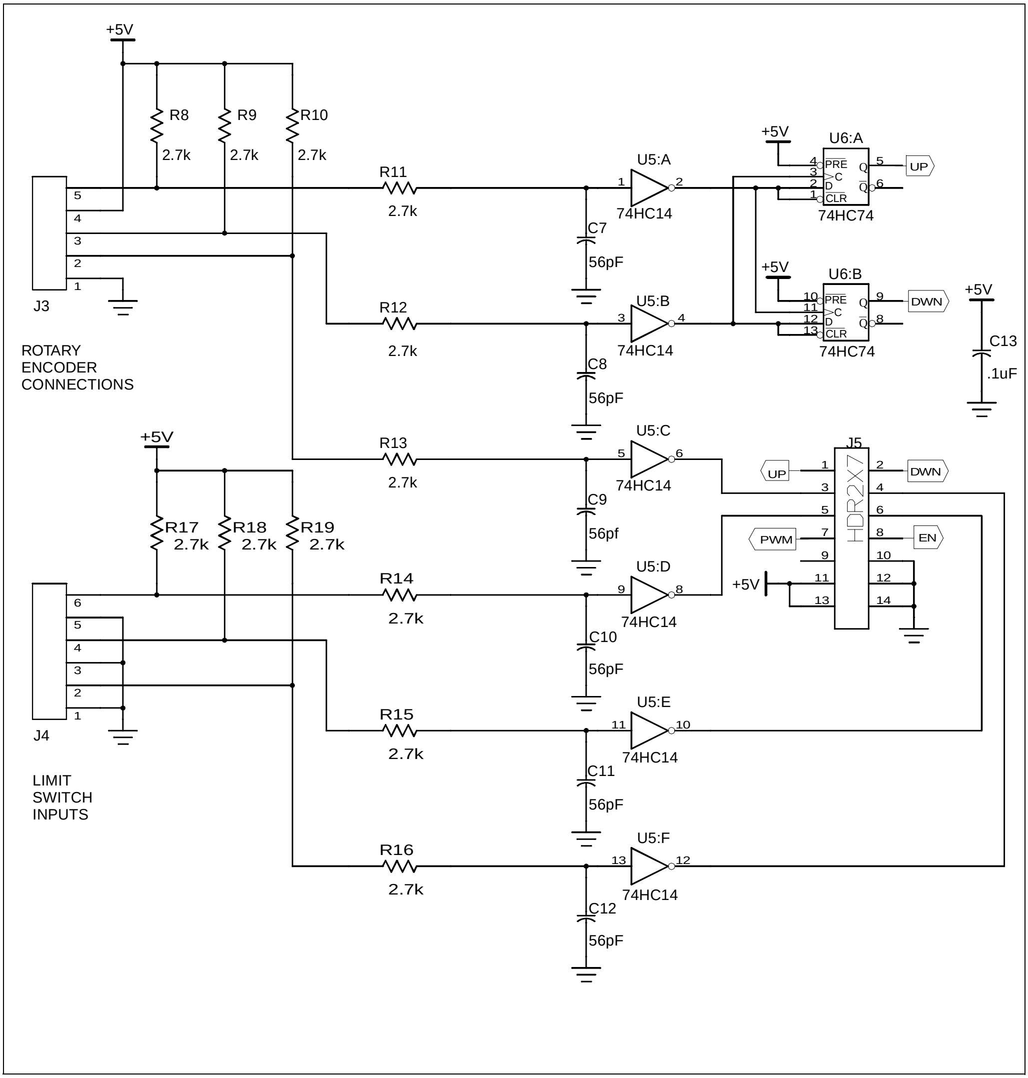


FIGURE A-3: SCHEMATIC 3



APPENDIX B: SOURCE CODE

```
//--------------------------------------------------------------------
//              17motor.c
//              Written By:      Steve Bowling, Microchip Technology
//
//              This source code demonstrates the use of the PIC17C756A in a
//              brush-DC servomotor application and is written for the MPLAB-C17
//              compiler.  The following files should be included in the C17
//              project, which is compiled for the large memory model:
//
//              17motor.c        --
//              c0l17.o          --       startup code
//              idata17.o        --       initialized data support
//              p17c756.o        --       processor definition module
//              int756l.o        --       interrupt handler routines
//              pmc756l.lib      --       library functions
//              p17c756l.lkr     --       linker script
//
//--------------------------------------------------------------------

#include <p17c756.h>
#include <stdlib.h>
#include <usart16.h>
#include <string.h>
#include <timers16.h>
#include <captur16.h>
#include <pwm16.h>
#include <ctype.h>
#include <delays.h>
#include <mem.h>

#define  F  1
#define  W  0

const rom char start[] = “\r\n\r\n17C756A DC Servomotor”;
const rom char ready[] = “\n\rREADY>”;
const rom char error[] = “\n\rERROR!”;

char inpbuf[8];                              // input buffer for ASCII commands
char data[9];                                // buffer for ASCII conversions
char command;                                // holds the last parameter change
                                             // command that was received

unsigned char
i,                                           // index to ASCII buffer
udata,                                       // received character from USART
mode,                                        // determines servo mode
tempchar,
PRODHtemp,                                   // temp context saving for ISR
PRODLtemp,                                   // “
FSR0temp,                                    // “
FSR1temp;                                    // “

struct {                                     // holds status bits for servo
    unsigned            phase:1;             // first half/ second half of profile
    unsigned         neg_move:1;             // backwards relative move
    unsigned move_in_progress:1;             //
    unsigned   saturated:1;                  // servo output is saturated
    unsigned          bit4:1;
    unsigned              bit5:1;
    unsigned             bit6:1;
    unsigned             bit7:1;
} stat ;

int
```

```
tempint3,                                   //
tempint2,                                   //
tempint1,                                   //
tempint0,                                   //
UpCount,                                    // encoder up counts during sample period
DnCount,                                    // encoder down counts “      “      “
u0,u1,                                      // current and previous position error
kp,ki,kd,                                   // PID gain constants
integral,                                   // PID error accumulation
ypwm,                                       // duty cycle derived from PID calculation
multcnd,multplr,                            // holds values to be multiplied in mult()
velcom,vlim;                                // commanded velocity, velocity limit

unsigned int accel;                         // acceleration parameter for motion profile

union LONG
{
unsigned int ui[2];
int i[2];
char b[4];
};

union LONG
aarg,                                       // Used for math calculations.
barg,                                       //              “
ypid,                                       // Used to hold result of the PID
                                            // calculations.
position,                                   // Commanded position.
mposition,                                  // Actual measured position.
fposition,                                  // Final commanded position of motion
                                            // profile.
poserror,                                   // 32-bit position error calculated
                                            // in the PID
mvelocity,                                  // measured velocity
velact,                                     // current commanded velocity
phase1dist,                                 // total distance for first half of move.
flatcount;                                  // Holds the number of sample periods for
                                            // which the velocity limit was reached in
                                            // the first half of the move.


//  Function Declarations----------------------------------------------

void main(void);                            // Required for the main function
void InitPorts(void);                       // Initializes ports/peripherals
void InitVars(void);                        // Initializes variable used in program
void DoCommand(void);                       // Parses input buffer after a <CR> was received
void ServoISR(void);                        // Performs the error calculations and PID
void UpdatePosition(void);                  // Updates the measured motor position
void UpdateTrajectory(void);                // Does the motion profile
void add32(void);                           // Performs a 32 bit addition
void sub32(void);                           // Performs a 32 bit subtraction
void mult(void);                            // Performs a 16 x 16 --> 32 multiplication
void ulitoa(unsigned int value1,            // Converts 32-bit value in two integers
unsigned int value0, char *string);         // to an ASCII string in hexadecimal
char ntoh(unsigned int value);              // format.


//---------------------------------------------------------------------


void main(void)
{
InitVars();
InitPorts();
Install_PIV(ServoISR);                      // Servo_ISR is installed as the
```

```
                                                // peripheral
Enable();                                       // int. handler.

putrsUSART1(start);
putrsUSART1(ready);

while(1)                                        // This is the main program loop
   {                                            // that polls USART1 for received
                                                // characters.
   if(PIR1bits.RC1IF)
      {
      switch(udata = ReadUSART1())
         {
         case 0x0d:  DoCommand();               // got a <CR>, so process the string
                     strset(inpbuf, 0);         // clear the input buffer
                     i = 0;                     // clear the input buffer index
                     putrsUSART1(ready);        // put a ready prompt on the screen
                     break;

         default:    inpbuf[i] = udata;         // put the received character in the
                     i++;                       // next buffer location and increment
                     if(i > 7)                  // the buffer index
                        {
                        putrsUSART1(ready);     // if we got more than 7 chars before a
                        strset(inpbuf, 0);      // <CR>, clear the input buffer and clear
                        i = 0;                  // the buffer index
                        }
                     else putcUSART1(udata);    // otherwise, echo the received character
                     break;                     //

         }                                      //end switch(udata)

      }                                         //end if(PIR1bits.RC1IF)


   }                                            //end while(1)
}                                               //end main

//--------------------------------------------------------------------


void DoCommand(void)                            // This routine parses the input buffer
{                                               // after a <CR> was received.
unsigned int num;


if(isdigit(inpbuf[0]) ||  inpbuf[0] == '-')     // Did we get a numerical input?
   {
   if(command)                                  // Was numerical input preceded
      {                                         // by a command to change a
      switch(command)                           // parameter?
         {
         case 'P':   kp = atoi(inpbuf);         // proportional gain change
                     break;

         case 'I':   ki = atoi(inpbuf);         // integral gain change
                     break;

         case 'D':   kd = atoi(inpbuf);         // differential gain change
                     break;

         case 'A':   accel = atoui(inpbuf);     // acceleration change
                     break;

         case 'V':   vlim = atoui(inpbuf);      // velocity limit change
                     break;
```

```
      case ‘S’:   PR2 = atoub(inpbuf);      // servo update timing change
                  break;

      default:    break;

      }
    command = 0;
    }

  else if(mode == 0) ypwm = atoi(inpbuf);     // manual mode:  write directly to PWM

  else if(mode == 1) velcom = atoi(inpbuf);   // velocity mode:  input data is velocity

  else if(mode == 2)                          // Input data is a relative movement
                                              // distance
    {                                         // distance for position mode.
    if(!stat.move_in_progress)                // Make sure no move is in progress.
      {
      phase1dist.i[1] = atoi(inpbuf);         // Load the 16-bit relative movement
                                              // distance into the upper
      phase1dist.i[0] = 0;                    // two bytes of phase1dist variable

      fposition.i[0] = position.i[0];         // Final position is commanded position
      fposition.i[1] = position.i[1]          // + relative move distance
                     + phase1dist.i[1];

      if(phase1dist.b[3] & 0x80)              // If the relative move is negative,
        {
        stat.neg_move = 1;                    // set flag to indicate neg. move

        _asm                                  // and covert phase1dist to a positive
        comf      phase1dist+2,F              // value.
        comf      phase1dist+3,F
        clrf      WREG,F
        incf      phase1dist+2,F
        addwfc    phase1dist+3,F
        _endasm

        }
      else stat.neg_move = 0;                 // Clear the flag for a positive move.

      _asm                                    // phase1dist now holds the total
        rlcf  phase1dist+3,W                  // distance, so divide by 2
        rrcf  phase1dist+3,F
        rrcf  phase1dist+2,F
        rrcf  phase1dist+1,F
        rrcf  phase1dist+0,F
      _endasm

      flatcount.i[1] = 0;                     // Clear flatcount
      flatcount.i[0] = 0;

      stat.phase = 0;                         // Clear flag:  first half of move.
      stat.move_in_progress = 1;
      }
    }
  else;
  }

else switch(inpbuf[0])
  {
  case ‘K’:   if(inpbuf[1] == ‘P’) command = ‘P’;// If this is a parameter change,
              else                            // determine which parameter
              if(inpbuf[1] == ‘I’) command = ‘I’;
              else
```

```
            if(inpbuf[1] == 'D') command = 'D';
            else
            if(inpbuf[1] == 'A') command = 'A';
            else
            if(inpbuf[1] == 'V') command = 'V';
            else
            if(inpbuf[1] == 'S') command = 'S';
            break;

case 'W':   if(PORTFbits.RF4 == 0)
               {
               putrsUSART1("\r\nPWM ON");
               SetDCPWM1(512);
               }
            else
               {
               putrsUSART1("\r\nPWM OFF");
               }
            PORTF = PORTF ^ 0x10;          // enables or disables PWM amplifier
            break;

case 'R':   putrsUSART1("  Kp = ");        // Send all parameters to host.
            uitoa(kp, data);
            putsUSART1(data);

            putrsUSART1("  Ki = ");
            uitoa(ki, data);
            putsUSART1(data);

            putrsUSART1("  Kd = ");
            uitoa(kd, data);
            putsUSART1(data);

            putrsUSART1("  Vlim = ");
            uitoa(vlim, data);
            putsUSART1(data);

            putrsUSART1("  Acc. = ");
            uitoa(accel, data);
            putsUSART1(data);

            break;

case 'M':   putrsUSART1(" Manual Mode");   // Put the servomotor in manual mode.
            SetDCPWM1(512);
            mode = 0;
            break;

case 'V':   putrsUSART1(" Velocity Mode"); // Put the servomotor in velocity mode.
            velcom = 0;
            SetDCPWM1(512);
            position = mposition;
            fposition = position;
            mode = 1;
            break;

case 'P':   putrsUSART1(" Position Mode"); // Put the servomotor in position mode.
            SetDCPWM1(512);
            position = mposition;
            fposition = position;
            mode = 2;
            break;

case 'L':   tempint0 = mposition.i[0];     // Send measured and commanded position
            tempint2 = position.i[0];      // to host.
            tempint1 = mposition.i[1];
```

```
              tempint3 = position.i[1];
              ulitoa(tempint1,tempint0,data);
              putrsUSART1(“ Measured = “);
              putsUSART1(data);
              ulitoa(tempint3,tempint2,data);
              putrsUSART1(“  Commanded = “);
              putsUSART1(data);
              break;

   case ‘Z’:  if(!stat.move_in_progress)      // Set measured position to 0.
                 {
                 if(mode) CloseTimer2();      // Disable interrupt generation.
                 position.i[1] = 0;
                 position.i[0] = 0;
                 mposition = position;
                 fposition = position;
                 WriteTimer0(0);
                 WriteTimer3(0);
                 mvelocity.i[1] = 0;
                 mvelocity.i[0] = 0;
                 UpCount = 0;
                 DnCount = 0;
                 if(mode) OpenTimer2(TIMER_INT_ON&T2_SOURCE_EXT);// Enable Timer2
                 }

              putrsUSART1(ready);
              break;

   default:   if(inpbuf[0] != ‘\0’)
                 {
                 putrsUSART1(error);
                 }
              break;

   }

}

//----------------------------------------------------------------------


void ServoISR(void)
{
PRODHtemp = PRODH;                            // Save context for necessary registers
PRODLtemp = PRODL;
FSR0temp = FSR0;
FSR1temp = FSR1;

UpdatePosition();                             // Get new mposition, mvelocity values

if(mode)                                      // This portion of code not executed
       {                                      // in manual mode.
       UpdateTrajectory();                    // Do trajectory algorithm to get new
                                              // commanded position.
       aarg = position;                       // Subtract measured position
       barg = mposition;                      // from commanded position
       sub32();                               // to get 32 bit position error.

       poserror.b[2] = aarg.b[3];             // LSByte holds fractional encoder counts,
       poserror.b[1] = aarg.b[2];             // so shift everything right.
       poserror.b[0] = aarg.b[1];

       if (poserror.b[2] & 0x80)              // If position error is negative.
          {
          poserror.b[3] = 0xff;               // Sign-extend to 32 bits.
```

```
        if((poserror.i[1] != 0xffff) || !(poserror.b[1] & 0x80))
           {
           poserror.i[1] = 0xffff;           // Limit error to 16-bit signed integer
           poserror.i[0] = 0x8000;
           }
        else;
        }

     else                                    // If position error is positive.
        {
        poserror.b[3] = 0x00;

        if((poserror.i[1] != 0x0000) || (poserror.b[1] & 0x80))
           {
           poserror.i[1] = 0x0000;           // Limit error to 16-bit signed integer.
           poserror.i[0] = 0x7fff;
           }
     else;
        }

        u0 = poserror.i[0];                  // Put position error in u0.

        multcnd = u0;                        // Calculate proportional term
        multplr = kp;                        // of PID
        mult();
        ypid = aarg;

        if(!stat.saturated) integral +=u0;   // Bypass integration if saturated.

        multcnd = integral;                  // Calculate integral term of PID
        multplr = ki;
        mult();
        barg = ypid;
        add32();                             // Add integral term.
        ypid = aarg;

        multcnd = u0 - u1;                   // Calculate differential term of PID
        multplr = kd;
        mult();
        barg = ypid;                         // Add differential term
        add32();
        ypid = aarg;

        if(ypid.b[3] & 0x80)                 // If PID result is negative
           {
           if((ypid.b[3] < 0xff) || !(ypid.b[2] & 0x80))
              {
              ypid.i[1] = 0xff80;            // Limit result to 24-bit value
              ypid.i[0] = 0x0000;
              }
           else;
           }

        else                                 // If PID result is positive
           {
           if(ypid.b[3] || (ypid.b[2] > 0x7f))
              {
              ypid.i[1] = 0x007f;            // Limit result to 24-bit value
              ypid.i[0] = 0xffff;
              }
           else;
           }

        ypid.b[0] = ypid.b[1];               // Shift PID result right to get
        ypid.b[1] = ypid.b[2];               // upper 16 bits of 24-bit result in
        ypwm = ypid.i[0];                    // ypid.i[0]
```

```
          u1 = u0;                                    // Save current error in u1
          }                                           // end if(mode)

stat.saturated = 0;                                   // Clear saturation flag


if(ypwm > 500)
   {
   ypwm = 500;
   stat.saturated = 1;
   }
else if(ypwm < -500)
   {
   ypwm = -500;
   stat.saturated = 1;
   }

SetDCPWM1((unsigned int)(ypwm + 512));                // Write new duty cycle value

PRODH = PRODHtemp;                                    // Restore context.
PRODL = PRODLtemp;
FSR0 = FSR0temp;
FSR1 = FSR1temp;

PIR1bits.TMR2IF = 0;                                  // Clear flag that generated interrupt.
}

//-------------------------------------------------------------------
// The relative distance travelled during the sample period is found using
// the following formula:
//
// mvelocity = (Timer0 - prev. Timer0) - (Timer3 - prev. Timer3)
//
// This is done so the timers do not have to be cleared each sample period
// and potentially cause counts to be lost.
//


void UpdatePosition(void)
{
mvelocity.i[0] = DnCount;                             // Add previous Timer3 value
mvelocity.i[0] -= UpCount;                            // Subtract previous Timer0 value

UpCount = ReadTimer0();                               // get new values from Timer0
DnCount = ReadTimer3();                               // and Timer3

mvelocity.i[0] += UpCount;                            // Add current Timer0 value
mvelocity.i[0] -= DnCount;                            // Subtract current Timer3 value

mvelocity.b[2] = mvelocity.b[1];                      // Shift result left:  LSbyte is
mvelocity.b[1] = mvelocity.b[0];                      // fractional
mvelocity.b[0] = 0;

if (mvelocity.b[2] & 0x80)                            // Sign-extend result
    mvelocity.b[3] = 0xff;
else
    mvelocity.b[3] = 0;

aarg = mposition;                                     // Add velocity to measured position
barg = mvelocity;
add32();
mposition = aarg;

}
```

```
//---------------------------------------------------------------------

void UpdateTrajectory(void)
{
if(mode == 1)                                   // If servomotor is in velocity mode.
   {
   if(!stat.saturated)                          // Don't update profile if saturated.
      {
      if(velact.i[1] < velcom)                  // If current velocity is less than
         {                                      // commanded velocity.
         aarg = velact;
         barg.i[0] = accel;                     // Accelerate
         barg.i[1] = 0;
         add32();
         velact = aarg;

         if(velact.i[1] > velcom)               // Don't exceed commanded velocity
         velact.i[1] = velcom;

         if(velact.i[1] > vlim)                 // Don't exceed velocity limit parameter
         velact.i[1] = vlim;
         }
      else
      if(velact.i[1] > velcom)                  // If current velocity exceeds commanded
         {                                      // velocity
         aarg = velact;
         barg.i[0] = accel;                     // Decelerate
         barg.i[1] = 0;
         sub32();
         velact = aarg;
         if(velact.i[1] < velcom)               // Don't exceed commanded velocity
         velact.i[1] = velcom;
         if(velact.i[1] < -vlim)                // Don't exceed velocity limit parameter
         velact.i[1] = -vlim;
         }
      else;

      aarg = position;                          // Add current commanded velocity to
      barg.i[0] = velact.i[1];                  // the commanded position
      if(velact.b[3] & 0x80)
      barg.i[1] = 0xffff;
      else barg.i[1] = 0;
      add32();
      position = aarg;
      }
   }

else if(mode == 2)
   {                                            // If we're in position mode.
   if(!stat.saturated)                          // Don't update profile if output is
                                                // saturated
      {
      if(!stat.phase)                           // If we're in the first half of the move.
         {
         if(velact.i[1] < vlim)                 // If we're still below the velocity limit
            {                                   // for the move
            aarg = velact;
            barg.i[0] = accel;
            barg.i[1] = 0;
            add32();
            velact = aarg;
            }
         else                                   // If we're at the velocity limit,
            {                                   // increment flatcount to keep track of
            _asm                                // time spent in flat portion of
            clrf     WREG,F                     // trajectory.
```



```
            incf     flatcount+0,F
            addwfc   flatcount+1,F
            addwfc   flatcount+2,F
            addwfc   flatcount+3,F
            _endasm
            }

         aarg = phase1dist;                     // go ahead and subtract the current
         barg.i[1] = 0;                         // velocity from the move distance to keep
         barg.i[0] = velact.i[1];               // track of the number of encoder counts
         sub32();                               // travelled during this sample period.
         phase1dist = aarg;

         aarg = position;                       // Add the current velocity to the
                                                // commanded position.
         if(stat.neg_move) sub32();
         else add32();
         position = aarg;

         if(phase1dist.b[3] & 0x80)             // If phase1dist has gone negative, the
         stat.phase = 1;                        // first half of the move has completed

         }

      else                                      // If we’re in the second half of the
                                                // move.
         {
         if(flatcount.i[1] || flatcount.i[0])
            {
            _asm                                // If flatcount is not zero, decrement it.
            clrf     WREG,F
            decf     flatcount+0,F
            subwfb   flatcount+1,F
            subwfb   flatcount+2,F
            subwfb   flatcount+3,F
            _endasm
            }
         else
         if(velact.i[1])                        // If velact is not 0, decelerate.
            {
            aarg = velact;
            barg.i[0] = accel;
            barg.i[1] = 0;
            sub32();
            velact = aarg;
            }
         else                                   // flatcount is 0, velact is 0, so move is
            {                                   // over.  Set commanded position equal to
            position = fposition;               // the final position calculated at the
            stat.move_in_progress = 0;          // beginning of the move.
            }

         aarg = position;                       // Add current velocity to commanded
                                                // position.
         barg.i[1] = 0;
         barg.i[0] = velact.i[1];
         if(stat.neg_move) sub32();
         else add32();
         position = aarg;
         }
      }                                         // END if(!stat.saturated)
   }                                            // END if(mode == 2)

else;

}
```

```
//-------------------------------------------------------------------

void add32(void)                              //
{
_asm

   MOVFP    barg+0,WREG
   ADDWF    aarg+0,F
   MOVFP    barg+1,WREG
   ADDWFC   aarg+1,F
   MOVFP    barg+2,WREG
   ADDWFC   aarg+2,F
   MOVFP    barg+3,WREG
   ADDWFC   aarg+3,F

_endasm
}

//-------------------------------------------------------------------

void sub32(void)                              //
{
_asm

   MOVFP    barg+0,WREG
   SUBWF    aarg+0,F
   MOVFP    barg+1,WREG
   SUBWFB   aarg+1,F
   MOVFP    barg+2,WREG
   SUBWFB   aarg+2,F
   MOVFP    barg+3,WREG
   SUBWFB   aarg+3,F

_endasm
}

//-------------------------------------------------------------------

void mult(void)                               // Multiplies 16-bit values in multplr
{                                             // and multend.
_asm                                          // 32-bit result is stored in aarg

   movfp    multcnd+0,WREG
   mulwf    multplr+0
   movpf    PRODH,aarg+1
   movpf    PRODL,aarg+0

   movfp    multcnd+1,WREG
   mulwf    multplr+1
   movpf    PRODH,aarg+3
   movpf    PRODL,aarg+2

   movfp    multcnd+0,WREG
   mulwf    multplr+1

   movfp    PRODL,WREG
   addwf    aarg+1,F
   movfp    PRODH,WREG
   addwfc   aarg+2,F
   clrf     WREG,F
   addwfc   aarg+3,F

   movfp    multcnd+1,WREG
   mulwf    multplr+0
```

```
   movfp    PRODL,WREG
   addwf    aarg+1,F
   movfp    PRODH,WREG
   addwfc   aarg+2,F
   clrf     WREG,F
   addwfc   aarg+3,F

   btfss    multplr+1,7
   goto     $ + 5
   movfp    multcnd+0,WREG
   subwf    aarg+2,F
   movfp    multcnd+1,WREG
   subwfb   aarg+3,F

   btfss    multcnd+1,7
   goto     $ + 5
   movfp    multplr+0,WREG
   subwf    aarg+2,F
   movfp    multplr+1,WREG
   subwfb   aarg+3,F

   nop
_endasm
}

//----------------------------------------------------------------------

void ulitoa(unsigned int value1, unsigned int value0, char *string)
{
unsigned int temp;                              // Converts 32-bit value stored in two
                                                // integers to an ASCII string in
temp = value1;                                  // hexidecimal format.
*string = ntoh(temp >> 12);
string++;

temp = value1 & 0x0f00;
*string = ntoh(temp >> 8);
string++;

temp = value1 & 0x00f0;
*string = ntoh(temp >> 4);
string++;

temp = value1 & 0x000f;
*string = ntoh(temp);
string++;

temp = value0;
*string = ntoh(temp >> 12);
string++;

temp = value0 & 0x0f00;
*string = ntoh(temp >> 8);
string++;

temp = value0 & 0x00f0;
*string = ntoh(temp >> 4);
string++;

temp = value0 & 0x000f;
*string = ntoh(temp);
string++;

*string = 0;

return;
```

```
}

//---------------------------------------------------------------------

char ntoh(unsigned int value)                  // Converts hexidecimal value to ASCII
{                                              // value.
char hexval;

if(value < 10) hexval = value + '0';
else if(value < 16) hexval = value - 10 + 'A';

return hexval;
}

//---------------------------------------------------------------------

void InitVars(void)
{
i = 0;

kp = 2000;
ki = 15;
kd = 6000;

vlim = 4096;
velcom = 0;
velact.i[1] = 0;
velact.i[0] = 0;
accel = 65535;

integral = 0;
mvelocity.i[1] = 0;
mvelocity.i[0] = 0;
UpCount = 0;
DnCount = 0;
position = mposition;
fposition = position;

stat.move_in_progress = 0;
stat.neg_move = 0;
stat.phase = 1;

mode = 0;
ypwm = 0;

strset(inpbuf,'\0');
}

//---------------------------------------------------------------------

void InitPorts(void)
{
ADCON1 = 0x0E;                                 // ensure port F is configured for
                                               // digital IO.
PORTF = 0x00;                                  // ensure port F is 0 before setting data
                                               // direction.
DDRF = 0x0f;                                   // RF<7:4> outputs, RF<3:0> inputs

PORTFbits.RF4 = 0;                             // ensure pwm amplifier is disabled!!!

// Up/Down Register Setup -----------------------

WriteTimer0(0);
WriteTimer3(0);
OpenTimer0(TIMER_INT_OFF&T0_EDGE_FALL&T0_SOURCE_EXT&T0_PS_1_1);
OpenTimer3(TIMER_INT_OFF&T3_SOURCE_EXT);
```

```
TCON2bits.CA1 = 1;

// PWM Setup -----------------------------------

OpenTimer1(TIMER_INT_OFF&T1_SOURCE_INT&T1_T2_8BIT);// set up timer1 for PWM timebase
OpenPWM1(0xff);                               // start up PWM1
SetDCPWM1(512);                               // set the initial PWM duty cycle
                                              // to ~50%


PR2 = 0x08;                                   // Set Timer2 overflow period to 8
                                              // for 3.9 kHz update at 33 MHz
OpenTimer2(TIMER_INT_ON&T2_SOURCE_EXT);       // Enable Timer2

// USART1 Setup --------------------------------

OpenUSART1(USART_TX_INT_OFF&USART_RX_INT_OFF&USART_ASYNCH_MODE&
           USART_EIGHT_BIT&USART_CONT_RX, 26); // open the serial port
                                              // 19.2 kbaud @ 33 Mhz
}
```

NOTES:

NOTES:

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- The PICmicro family meets the specifications contained in the Microchip Data Sheet.
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