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April 1st, 2010
Renesas Electronics Corporation

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H8/300L SLP Series
Precise Control of DC Motor (DCmotor)

Introduction
This application note demonstrates how to use the H8/38024 SLP series to control a brush-DC servomotor. Advantages of using the H8/38024 SLP MCU are the many built-in peripherals such as the PWM, Serial Communication Interface (SCI), Timers, etc. This servomotor system can be used as the position controller in a printer, plotter or scanner.

Target Device
H8/38024

Contents
1. Introduction ................................................................................................................... 2
2. System Overview ......................................................................................................... 3
3. Hardware Implementation ............................................................................................ 4
4. Software Implementation ............................................................................................. 7
5. Hardware Schematics .................................................................................................. 31
6. References .................................................................................................................. 37
1. **Introduction**

There are three types of single supply brushed DC motors

- Series wound (unidirectional)
- Shunt wound (bi-directional by changing connections)
- Permanent magnet (bi-directional by reversing current)

In this application note, the permanent magnet DC motor is used. The stator of the motor is composed of two or more permanent magnet pole pieces while the rotor is composed of windings that are connected to a mechanical commutator. The opposite end polarities of the energized windings and the stator magnet attract and the rotor will rotate until it is aligned with the stator. Just at the instant where the rotor reaches alignment, the brushes move the commutator contacts and energize the next winding.

![Block Diagram of Permanent Magnet DC Motor](image)

The advantages and disadvantages of DC motors are summarized in table 1.

### Advantages and Disadvantages of DC Motors

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy to control</td>
<td>Requires maintenance</td>
</tr>
<tr>
<td>Efficient</td>
<td>Cannot be used in certain hazardous environments</td>
</tr>
<tr>
<td>Smaller than induction motors of the same power</td>
<td>Noisier than induction motors</td>
</tr>
<tr>
<td>Fewer components required for speed control</td>
<td>Lower horsepower (HP)</td>
</tr>
</tbody>
</table>
2. System Overview

The block diagram of the servomotor system described in this application note is shown in Figure 2. The system is comprised of the following components:

- H8/38024 SLP MCU
- RS-232C Interface
- Full-bridge PWM Motor Driver
- Faulhaber Brush-DC Motor with Optical Encoder

In this application note, the roles of the MCU are as follows:

- measure the motor position
- generate the speed profile
- calculate the compensation algorithm
- produce the drive signal to the PWM motor driver
- transmit the desired and actual speeds back to the PC through the RS-232 interface

One of the two available pulse-width modulation (PWM) modules with 10-bit resolution is used to generate the motor drive signal. The PWM frequency is 20 kHz at device operating frequency of 10 MHz. The torque applied to the motor is determined by duty cycle of the PWM signal. The PWM signal is connected to an H-bridge driver IC capable of delivering 1.3 A.

A Faulhaber brush-DC motor with optical encoder with the following characteristics shown in table 2 is used here:

### Motor Characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>No-load speed</td>
<td>9300</td>
<td>Rpm</td>
</tr>
<tr>
<td>Torque constant</td>
<td>6.10</td>
<td>MNm/A</td>
</tr>
</tbody>
</table>
3. Hardware Implementation

Table 3 summarizes the usage of peripherals.

**Peripheral Usage**

<table>
<thead>
<tr>
<th>Peripheral</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 6[7..0]</td>
<td>“Data” bus</td>
</tr>
<tr>
<td>Port 7[6..0]</td>
<td>“Address” bus</td>
</tr>
<tr>
<td>P77</td>
<td>WRITE/READ_N</td>
</tr>
<tr>
<td>SCI (TXD&lt;sub&gt;32&lt;/sub&gt; and RXD&lt;sub&gt;32&lt;/sub&gt;)</td>
<td>Communication with host PC</td>
</tr>
<tr>
<td>P90/PWM1</td>
<td>*PHASE</td>
</tr>
<tr>
<td>P92</td>
<td>*REF</td>
</tr>
<tr>
<td>P93</td>
<td>*ENABLE_N</td>
</tr>
<tr>
<td>P94</td>
<td>*MODE</td>
</tr>
<tr>
<td>P95</td>
<td>*BRAKE_N</td>
</tr>
<tr>
<td>Timer F</td>
<td>Servo update time-base</td>
</tr>
</tbody>
</table>

Note: Connected to the PWM motor driver (A3953SB). Refer to section 3.6 for details.

3.1 Power Supplies

Three separate supplies are required in this application example:

- 6 V for DC motor
- 5 V for 74HCT138, level shifter, alphanumeric display, quadrature encoder interface
- 3.3 V for MCU, RS-232 transceiver, level shifter, PWM motor driver

<table>
<thead>
<tr>
<th>Supply Voltage</th>
<th>LM1117DTX-5.0</th>
<th>LM1117DTX-3.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>6V</td>
<td>5V Regulator</td>
<td>3.3V Regulator</td>
</tr>
<tr>
<td>5V</td>
<td>3V3</td>
<td></td>
</tr>
</tbody>
</table>

Power Supplies

3.2 Address and Data Buses

To allow the H8/38024 SLP MCU to access memory-mapped external devices/memories/peripherals, separate address and data buses with control signal WRITE/READ_N are constructed using general I/O ports as shown in figure 4. The MCU is operating at 3.3 V while some devices operate at 5 V. The function of the level shifters is to interface the MCU to the 5-V devices.
3.3 Address Decoder

A 74HCT138 3 to 8 line decoder is used here to select the memory-mapped devices namely, the Alphanumeric Intelligent Display (DLR1414) and the quadrature decoder. Table 4 lists the addresses.

### Address Mapping

<table>
<thead>
<tr>
<th>Address (Hexadecimal)</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>Encoder (high byte)</td>
</tr>
<tr>
<td>45</td>
<td>Encoder (low byte)</td>
</tr>
<tr>
<td>C0</td>
<td>Display (first digit)</td>
</tr>
<tr>
<td>C1</td>
<td>Display (second digit)</td>
</tr>
<tr>
<td>C2</td>
<td>Display (third digit)</td>
</tr>
<tr>
<td>C3</td>
<td>Display (fourth digit)</td>
</tr>
<tr>
<td>C8</td>
<td>Reset encoder</td>
</tr>
</tbody>
</table>

3.4 RS-232C Transceiver

The Serial Communication Interface (SCI) pins TXD\textsubscript{32} and RXD\textsubscript{32} are connected to the Sipex SP3232 RS-232C transceiver. This allows the MCU to communicate with the Host PC.

3.5 DC-Micromotor with Optical Encoder

The Faulhaber optical encoder (09BP series with 180 lines per revolution) is used in combination with the DC-Micromotor (2230 U 006 S series) for indication and control of both shaft velocity and direction of rotation, as well as positioning. Two LED sources transmit light through a metal disc with a number of light transmitting slits to give two channels (A and B) with a 90° phase shift as shown in Figure 5. For clockwise rotation, channel A leads channel B. Similarly, channel B leads channel A for counter-clockwise rotation.
The supply voltage for the motor and encoder as well as the two channel output signals are interfaced with a 150mm ribbon cable and a 10-pin connector as shown in figure 6.

The outputs from the encoder (channels A and B) are connected to the Agilent HCTL-2016 quadrature decoder, which consists of a 4x quadrature decoder, binary up/down 16-bit counter and bus interface function. The use of Schmitt-triggered CMOS inputs and input noise filters allows reliable operation in noisy environments.
The Allegro A3953SB is a full-bridge PWM motor driver designed for bi-directional pulse-width modulated current control of inductive loads. It can deliver continuous output currents of ±1.3A and operate at voltages up to 50V. The peak load current limit is set by the user’s selection of an input voltage reference voltage and external sensing resistor. The fixed off-time pulse duration is set by a user-selected external RC timing network. The internal circuit protection includes thermal shutdown with hysteresis, transient-suppression diodes, and crossover current protection.

With the ENABLE_N input held low, the PHASE input controls load current polarity by selecting the appropriate source and sink driver pair. When a logic low is applied to the BRAKE input, the braking function is enabled. This overrides ENABLE and PHASE to turn off both source drivers and turn on both sink drivers. This brake function can be used to dynamically brake brushed DC motors.

A 50% PWM duty cycle will produce zero motor torque. A 0% and 100% duty cycle will produce maximum torque in the reverse and forward direction, respectively.

4. Software Implementation

The source code is written in the C language for easy implementation and compiled using the free H8 Tiny/SLP toolchain (version 5.0.0) for HEW Version 2.2 (Release 15).

The functions of the source codes are as follows:

- Measurement of motor position
- Calculation for the compensator algorithm
- Generation of profile
- RS-232C communication

Figure 8 shows the flowchart of the main function where the I/O ports, SCI (38400bps, 1 stop bit, parity disabled), timers and PWM are initialized. Timer F Output Compare interrupt service routine is programmed to occur every 1.5 ms. The encoder value is read. The new trajectory value and PID values are computed and the PWM output is set. The desired and actual speeds are also transmitted back to the PC.
4.1 Encoder Feedback

Both speed and direction feedback can be derived from the optical encoder mounted on the motor shaft. The encoder output signals are processed by the HCTL-2016 4x quadrature encoder and then fed to a binary 16-bit up/down counter. The contents of the 16-bit counter are read through an 8-bit bus interface in 2 sequential bytes. The high byte (bits 15 to 8, SEL = 0) is read first followed by the lower byte (bits 7 to 0, SEL = 1). A positive number indicates clockwise rotation whereas a negative number indicates counter-clockwise rotation. Therefore, 1 revolution will produce $4 \times 180 = 720$ pulses.
The servo sample interval is selected to be 1.5ms, which means that the 16-bit counter is read every 1.5ms. Computation is then performed and the value is then output to the PWM driver. The speed and direction of rotation can be determined by differencing the current and previous 16-bit counter values. For example,

<table>
<thead>
<tr>
<th>Encoder Count</th>
<th>Speed (counts/sampling interval)</th>
<th>Direction of rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>Previous</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>900</td>
<td>100</td>
</tr>
<tr>
<td>-1095</td>
<td>-1000</td>
<td>-95</td>
</tr>
</tbody>
</table>

### 4.2 PID Controller

One problem faced by the system designer is that load on the motor is subjected to change. Other factors such as age, calibration and environment also affect the operation of the motor. Consequently, feedback mechanisms are typically employed to control the motor speed. The Proportional-Integral-Derivative (PID) controller is commonly used. In this example, the reference signal r(n) indicates the desired motor speed. The actual motor speed (subject to change based on load), is measured by the optical encoder mounted on the motor.

The Proportional-Integral-Derivative controller is described by:

\[ u(t) = K_p \cdot e(t) + K_i \cdot e_i \cdot T + K_d \cdot \frac{d(e)}{dt} \]

where

- \( K_p \) is the proportional gain
- \( K_i \) is the integral gain
- \( K_d \) is the derivative gain
- \( T \) is the sampling interval
- \( e(t) \) is the error signal and equal to the difference between the desired and measured speeds

The proportional term considers only the difference between the present reference value and the actual speed being measured. This term is weighted by a gain factor, \( K_p \), derived using knowledge of the specific motor under control. The integral term considers the summation of all the errors that have been measured previously. This term serves to smooth out oscillations by damping the system. For example, when the measured speed is slightly less than the desired speed, the proportional term would resolve to increase the applied power, speeding up the motor. If the last few measurements indicate the motor to be too fast, the integral term would reduce or even prevent the introduction of more power. In addition, the integral term eliminates accumulated error. Since the amount of energy introduced by the proportional term is proportional to the amount of error (deviation of actual motor speed from the desired motor speed), its influence is very small when the motor is close to the desired speed. When a very small error has existed for many iterations of the PID loop, the integral term will accumulate and produce a control change to correct that error.
The derivative term considers the rate of change at which the error is changing and helps to improve settling time. When the actual motor speed is far below its target speed, we would like to accelerate faster. If the acceleration of the motor is constant, then the rate of error changes will be constant too (i.e., the differential term). We would like to see the differential term increase to some constant value. When we approach the target speed, we would like to reduce the rate at which the motor is increasing its speed to prevent overshooting i.e., differential term decrease to zero.

The integral term is described in discrete form as the summation of error terms measured at each sampling interval.

\[ e_i \cdot T = \sum_{j=0}^{i} (R_j - Y_j) \]

Similarly, the differential term can be discretely approximated as:

\[ \frac{de}{dt} = \frac{(e_n - e_{n-1})}{T} \]

where \( e_n \) and \( e_{n-1} \) are error signals calculated from the current and previous measurements.

This allows the PID to be approximated in discrete form as:

\[ u(n) = K_p \cdot e(n) + K_i \cdot \sum_i e_i \cdot T + K_d \cdot \frac{[e(n) - e(n-1)]}{T} \]

**4.3 Profile Generation**

A trajectory generation is essential for motion control. A linear piecewise velocity generation is implemented in this application. The velocity is incremented by a constant value until a specified maximum velocity is maintained. This maximum velocity is maintained until 70% of the total rotation has been covered. The velocity is then decremented by the same deceleration value until the minimum velocity is reached. Once the motor has reached the required rotation, position control is then utilized to hold the motor in position (braking function).
4.4 RS-232C Communications

The function of the RS-232C communications is to transmit the desired and actual speeds in (counts/sampling interval) to the PC. Using any terminal emulation software such as Tera Term Pro, these values are then sent to EXCEL and the response is plotted below as shown in figure 11. By altering the various gains and plotting the results, the system can be fine-tuned.

4.5 PID Tuning

When designing a PID controller for a given system, follow the steps below to obtain the desired response.

- Set the PID controller to proportional mode only i.e., $K_i$ and $K_d$ are set to 0.
- Set the proportional gain ($K_p$) to a small value to limit the output so that the servomotor system will not spin out of control initially. Safety concerns should be considered especially if the motor is to be used for driving some machinery, etc.
- Set a small reference value and observe the response of the controlled variable, for example the speed or position of the motor.
- Set $K_p$ to the point that will bring the system to the reference quickly without overshoot.
- Incorporate the integral gain ($K_i$) to eliminate the steady state error
- Include the derivative gain ($K_d$) to improve the transient response.
- Adjust the gains ($K_p$, $K_i$, $K_d$) until the desired response is obtained.
4.6 Source Codes

The source codes are mainly in the following files

- **Dcmotor.c**
  - Contains the main function
  - Performs initialization of the I/O ports, SCI, timers and PWM channel.
  - Generation of trajectory, display of encoder count, computation of PID values, speed and position control

- **int_prg.c**
  - Contains the Timer F Output Compare Interrupt Service Routine
  - Update the position count

For example, to program the motor to rotate 1 complete revolution in the counter-clockwise direction, the following constants defined in “Dcmotor.c” have to be set:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| distance_reference | -720  | 1° → 2 counts
|                    |       | 1 revolution → 360° → (360 * 2) = 720 counts
|                    |       | Negative for counter-clockwise direction                    |
| maximum_speed_reference | -7     | Maximum reference speed during acceleration/cruise          |
|                    |       | Negative for counter-clockwise direction                    |
| minimum_speed_reference | -1     | Minimum reference speed during deceleration                 |
|                    |       | Negative for counter-clockwise direction                    |
| speed_adjustment   | -1    | Step adjustment for reference speed                          |
|                    |       | Negative for counter-clockwise direction                    |
| proportional_gain  | 6     | Proportional gain for PID controller                         |
| integral_gain      | 2     | Integral gain for PID controller                             |
| derivative_gain    | 4     | Derivative gain for PID controller                           |
#ifndef __cplusplus
extern "C" {
#endif

#include "iodefine.h"
#include <machine.h>

//----------------------------------------------------------------------
//Constant Declarations
//----------------------------------------------------------------------

//Constants for Address Decoder
#define first_digit    0xC0
#define second_digit   0xC1
#define third_digit    0xC2
#define fourth_digit   0xC3
#define enc_count_high 0x44
#define enc_count_low  0x45
#define reset_2016    0xC8
#define de_select    0x3F

//Constants for Motor Control
#define distance_reference  -720  //1 degree = 2 encoder counts
#define maximum_speed_reference -7  //negative for counter-clockwise
#define minimum_speed_reference -1  //negative for counter-clockwise
#define speed_adjustment -1  //negative for counter-clockwise
#define proportional_gain  6
#define integral_gain  2
#define derivative_gain  4
#define max_pos_con_val  256

//Others
#define address_bus    P_IO.PDR7.BYTE //Address Bus
#define data_bus     P_IO.PDR6.BYTE //Data Bus

#ifdef __cplusplus
}
#endif
// Function Prototypes

void init_sci(void);
void char_put(char);
void PutStr(char *);

void init_port(void);
void display_char(unsigned char, unsigned char);
void init_timers(void);
void display_word(unsigned int);
void reset_encoder(void);
int read_encoder(void);
void init_pwm(void);
void serial_transmit(unsigned int);
void speed_control(void);
void speed_profile(void);
void position_control(void);

// 16-bit number: +ve for clockwise, -ve for counter-clockwise
int encoder_count, current_encoder_count, previous_encoder_count;

// 16-bit number: reference speed: +ve for clockwise, -ve for counter-clockwise
int speed_reference;
int current_speed;
int current_speed_error, previous_speed_error, sum_speed_error,
    diff_speed_error;
int speed_control_output;

int position_reference, position_reference_a;
int current_position_error, previous_position_error, sum_position_error,
    diff_position_error;
int position_control_output;

int speed_increment;   // +ve for clockwise, -ve for counter-clockwise
int max_speed_reference; // +ve for clockwise, -ve for counter-clockwise
int min_speed_reference; // +ve for clockwise, -ve for counter-clockwise
int temp_encoder_count, temp_position_reference;
unsigned int position_control_count;

static unsigned char reference_step = 0;

int kp_gain, ki_gain, kd_gain;

unsigned char start_position_control;

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

void main(void)
{
    //-------------------------------------------------------------

    init_port();

    init_sci();

    init_timers();

    init_pwm();

    reset_encoder();

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

    speed_reference = 0;

    speed_increment = speed_adjustment;

    max_speed_reference = maximum_speed_reference;

    min_speed_reference = minimum_speed_reference;

    previous_speed_error = 0;

    sum_speed_error = 0;

    diff_speed_error = 0;

    kp_gain = proportional_gain;

    ki_gain = integral_gain;

    kd_gain = derivative_gain;

    position_reference = distance_reference;

    position_reference_a = ((position_reference * 7) / 10);

    if (position_reference < 0)
    {
        position_reference_a = 0 - position_reference_a;
    }

    current_position_error = 0;

    previous_position_error = 0;

    sum_position_error = 0;

    start_position_control = 0;
position_control_count = 0;

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

P_SYSCR.IENR2.BIT.IENTFH = 1;  //Enable Timer FH interrupt requests

//if Timer FH interrupt request flag (IRRTFH) is set, clear to 0
if (P_SYSCR.IRR2.BIT.IRRTFH == 1)
    P_SYSCR.IRR2.BIT.IRRTFH = 0;

set_imask_ccr(0);     //Clear IMASK

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

while (1)
{
    
}

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

void abort(void)
{

}

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

/*
  init_pwm()
*/

void init_pwm(void)
{
    P_PWM1.PWCR1.BYTE = 0xFD;    //Conversion period is 1024/phi
    P_PWM1.PWDRL1.BYTE = 0x00;  //Write to lower 8 bits
    P_PWM1.PWDRU1.BYTE = 0xFE;  //Write to upper 2 bits
    P_IO.PDR9.BYTE &= 0xF7;   //Port 9[3] : Clear ENABLE_N
}

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

/*
  reset_encoder(): Reset encoder counts
*/

void reset_encoder(void)
{
    P_IO.PCR6.BYTE = 0xFF;    //Set Port 6[7..0] as output
}
address_bus &= de_select;
address_bus = reset_2016;
address_bus &= de_select;
}

/*------------------------------------------------------------------------------
*/
/*
  read_encoder(): Read encoder counts
*/

int read_encoder(void)
{
  int    counts;
  unsigned char low_byte, high_byte;

  P_IO.PCR6.BYTE = 0x00;   //Set Port 6[7..0] as input
  address_bus &= de_select;
  address_bus = enc_count_high;  //Address
  high_byte = data_bus;   //Data
  address_bus &= de_select;
  address_bus = enc_count_low;  //Address
  low_byte = data_bus;   //Data
  address_bus &= de_select;

  counts = (int)((high_byte << 8) | low_byte);
  return(counts);
}

/*------------------------------------------------------------------------------
*/
/*
  init_timers() : Set up Timer F
*/

void init_timers(void)
{
  //Timer Control Register F
  //TOLL = '1': Initial output for TMOFH is high
  //CKSH2 = '0', CKSH1 = '0', CKSH0 = '0': 16-bit mode, counting on TCFL
  //overflow signal
  //Clock input to TCFL at phi/4 i.e., (10MHz/2/4 = 1.25MHz)
  P_TMRF.TCRF.BYTE = 0x86;
// Timer Control/Status Register F
// CCLRH = '1': in 16-bit mode, TCF clearing by compare match is enabled
P_TMRF.TCSR.BYTE = 0x10;

// 1.5ms -> 0x753
P_TMRF.OCR.BYTE.H = 0x07;  // Output Compare Register FH
P_TMRF.OCR.BYTE.L = 0x53;  // Output Compare Register FL
}

/*-------------------------------------------------------------------------------
*/
void init_port(void)
{
P_IO.PMR3.BYTE = 0x04;    // P32 functions as TMOFH
P_LCD.LPCR.BYTE = 0x00;    // SEG[32..1] as I/O Port
P_IO.PCR6.BYTE = 0xFF;
P_IO.PCR7.BYTE = 0xFF;
P_IO.PDR6.BYTE = 0xFF;
P_IO.PDR7.BYTE = 0xFF;
P_IO.PMR9.BYTE = 0xF1;    // PWM1
}

/*-------------------------------------------------------------------------------
*/
void display_char(unsigned char digit_position, unsigned char digit_info)
{
P_IO.PCR6.BYTE = 0xFF;   // Set Port 6[7..0] as output

address_bus &= de_select;
data_bus = digit_info;  // Data
address_bus = digit_position;  // Address

address_bus &= de_select;

/*********************************************************************************
*/
/*
 * display_word()
 */

void display_word(unsigned int display_data)
{
    unsigned char position, digit_info, digit_position;
    P_IO.PCR6.BYTE = 0xFF;  // Set Port 6[7..0] as output
    for (position = 4; position != 0; position--)
    {
        switch (position)
        {
            case 1:
                digit_position = first_digit;
                digit_info = (unsigned char)(display_data & 0x000F);
                break;
            case 2:
                digit_position = second_digit;
                digit_info = (unsigned char)((display_data & 0x00F0) >> 4);
                break;
            case 3:
                digit_position = third_digit;
                digit_info = (unsigned char)((display_data & 0x0F00) >> 8);
                break;
            default:
                digit_position = fourth_digit;
                digit_info = (unsigned char)((display_data & 0xF000) >> 12);
                break;
        }

        if ((digit_info >= 0) && (digit_info <= 9))
            digit_info += 0x30;
        else
        {
            if ((digit_info >= 0xA) && (digit_info <= 0xF))
            {
                digit_info -= 0xA;
                digit_info += 0x41;
            }
        }
    }
address_bus &= de_select;
data_bus = digit_info; //Data
address_bus = digit_position; //Address
address_bus &= de_select;
}

//---serial_transmit()---------------------------------------------

/*
   serial_transmit()
*/

void serial_transmit(unsigned int display_data)
{
    unsigned char position, digit_info;

    for (position = 4 ; position != 0 ; position--)
    {
        switch (position)
        {
            case 1:
                digit_info = (unsigned char)(display_data & 0x000F);
                break;
            case 2:
                digit_info = (unsigned char)((display_data & 0x00F0) >> 4);
                break;
            case 3:
                digit_info = (unsigned char)((display_data & 0x0F00) >> 8);
                break;
            default:
                digit_info = (unsigned char)((display_data & 0xF000) >> 12);
                break;
        }
        if ((digit_info >= 0) && (digit_info <= 9))
            digit_info += 0x30;
        else
        {
            if ((digit_info >= 0xA) && (digit_info <= 0xF))
            {
                digit_info -= 0xA;
                digit_info += 0x41;
            }
        }
    }
}
char_put(digit_info);
} } }

/****************************************************************************

init_sci() : Sets up the Serial Communication Interface for debugging
purposes.
*/

void init_sci(void) {
    //SCR3 : |TIE|RIE|TE|RE|MPIE|TEIE|CKE1|CKE0|
    //TIE : Transmit interrupt enable
    //RIE : Receive interrupt enable
    //TE  : Transmit enable
    //RE  : Receive enable
    //MPIE : Multiprocessor interrupt enable
    //TEIE : Transmit end interrupt enable
    //CKE1 : Clock enable 1
    //CKE0 : Clock enable 0
    
    //CKE1 = CKE0 = 0
    //asynchronous mode, internal clock source, SCK32 functions as I/O port
    P_SCI3.SCR3.BYTE &= 0x00; //clear TE & RE
    
    //SMR : |COM|CHR|PE|PM|STOP|MP|CKS1|CKS0| : |0|0|0|0|0|0|0|0|
    //COM : Communication Mode : 0 : asynchronous mode
    //CHR : Character Length : 0 : character length = 8 bits
    //PE  : Parity Enable : 0 : parity bit addition and checking disabled
    //PM  : Parity Mode : 0 : even parity (no effect since parity is already disabled)
    //STOP: Stop Bit Length : 0 : 1 stop bit
    //MP  : Multiprocessor Mode : 0 : multiprocessor communication function disabled
    //|CKS1|CKS0| : Clock Select: |0|0| : clock source for baud rate generator
    = clk
    P_SCI3.SMR.BYTE = 0x00;

    //For clk = 10MHz, bit rate = 38400 bps, n = 0, N = 3
    P_SCI3.BRR = 3;

    //minimum of 1-bit delay = 417ns
    nop();
    nop();
    nop();

    //SPCR : |---|---|SPC32|---|SCINV3|SCINV2|---|---| : |1|1|1|0|0|0|0|0|
    //SPC32 = 1 : P42 functions as TXD32 output pin
    //need to set TE bit in SCR3 after setting this bit to 1
/SCINV3 = 0 : TXD32 output data is not inverted  
/SCINV2= 0 : RXD32 input data is not inverted  
// Bits 7 and 6 are reserved and always read as 1  
// Bits 4, 1 and 0 are reserved and only 0 can be written to these bits  
P_SCI3.SPCR.BYTE = 0xE0;

P_SCI3.SCR3.BYTE |= 0x30; // Set TE & RE

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

/*
 * char_put() : Transmits a character to the PC for debugging purposes.
 */

void char_put(char OutputChar)              // Serial Port  
{
  // SSR  : |TDRE|RDRF|OER|FER|PER|TEND|MPBR|MPBT|
  // TDRE : transmit data register empty  
  // RDRF : receive data register full  
  // OER  : overrun error  
  // FER  : framing error  
  // PER  : parity error  
  // TEND : transmit end  
  // MPBR : Multiprocessor bit receive  
  // MPBT : Multiprocessor bit transfer

  while ((P_SCI3.SSR.BIT.TDRE) == 0);     // Wait for TDRE = 1

  P_SCI3.TDR = OutputChar;

  while ((P_SCI3.SSR.BIT.TEND) == 0);     // Wait for TEND = 1

  P_SCI3.SSR.BIT.TEND = 0;
}

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

/*
 * PutStr() : Transmits a string of characters to the PC for debugging purposes.
 */

void PutStr(char *str)
{
  while (*str != 0)
  {
    char_put(*str++);
  }
}

//----------------------------------------------------------------------
 void speed_control(void)
{
   //---------------------------------------------
   previous_encoder_count = current_encoder_count;
   current_encoder_count = encoder_count;

   current_speed = current_encoder_count - previous_encoder_count;
   //---------------------------------------------

   serial_transmit(speed_reference);
   //---------------------------------------------

   previous_speed_error = current_speed_error;
   //---------------------------------------------

   current_speed_error = speed_reference - current_speed;

   PutStr("/");
   serial_transmit(current_speed);
   PutStr("\r\n");
   //---------------------------------------------

   sum_speed_error += (current_speed_error);
   diff_speed_error = (current_speed_error - previous_speed_error);
   //---------------------------------------------

   speed_control_output = (int)((kp_gain * current_speed_error) +
                                (sum_speed_error / ki_gain) +
                                (diff_speed_error * kd_gain));
   //---------------------------------------------

   //limit speed_control_output from -511 to +511
   if (speed_control_output > 511)
speed_control_output = 511;
else
{
    if (speed_control_output < -511)
        speed_control_output = -511;
}

//introduce offset of 512
speed_control_output += 512;

P_PWM1.PWDR1.BYTE = (unsigned char)(speed_control_output & 0x00FF);
//Write to lower 8 bits

P_PWM1.PWDRU1.BYTE = (unsigned char)((speed_control_output & 0xFF00)>> 8);
//Write to upper 2 bits

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

void speed_profile(void)
{
    int temp_encoder_count;

    reference_step++;

    temp_encoder_count = encoder_count;

    if (position_reference < 0)
        temp_encoder_count = 0 - encoder_count;

    if (temp_encoder_count > position_reference_a)
    {
        //decelerate
        if (reference_step > 7)
        {
            reference_step = 0;

            //For clockwise rotation, speed_increment is +ve
            //For counter-clockwise rotation, speed_increment is -ve

            //For example
            //a. clockwise, speed_increment = 1, speed_reference = 5 ->
            speed_reference = 5 - 1 = 4
            //b. counter-clockwise, speed_increment = -1, speed_reference = -5 ->
            speed_reference = -5 - (-1) = -4

            if (speed_reference < 0) //Counter-clockwise
{
    speed_reference -= speed_increment;
    if (speed_reference > min_speed_reference)
        speed_reference = min_speed_reference;
} else //Clockwise
{
    speed_reference -= speed_increment;
    if (speed_reference < min_speed_reference)
        speed_reference = min_speed_reference;
}
}
}
else
{
    //accelerate and cruise
    if (reference_step > 7)
    {
        reference_step = 0;

        //For clockwise rotation, speed_increment is +ve
        //For counter-clockwise rotation, speed_increment is -ve

        //For example
        //a. clockwise, speed_increment = 1, speed_reference = 5 ->
        speed_reference = 5 + 1 = 6
        //b. counter-clockwise, speed_increment = -1, speed_reference = -5 ->
        speed_reference = -5 + (-1) = -6
        speed_reference += speed_increment;

        if (speed_reference < 0) //Counter-clockwise
        {
            if (speed_reference < max_speed_reference)
                speed_reference = max_speed_reference;
        }
    }
    else //Clockwise
    {
        if (speed_reference > max_speed_reference)
            speed_reference = max_speed_reference;
    }
}

 Ủ ----- ---------------------------------------------------

<QString>

  position_control()
  1. position_error = reference_encoder_count - current_encoder_count

/*

  position_control()

  1. position_error = reference_encoder_count - current_encoder_count

*/
2. output = kp_gain * current_position_error 
   + sum(position_error) / ki_gain 
   + kd_gain * (position_error - previous_position_error);

   range-limited from -512 to 511

*/

void position_control(void)
{
    kp_gain = 10;
    ki_gain = 2;
    kd_gain = 3;

    position_control_count++;

    previous_position_error = current_position_error;

    current_position_error = position_reference - encoder_count;

    sum_position_error += (current_position_error);
    diff_position_error = (current_position_error - previous_position_error);

    position_control_output = (int)((kp_gain * current_position_error) +
    (kd_gain * diff_position_error));

    //limit position_control_output from -128 to +128

    if (position_control_output > max_pos_con_val)
        position_control_output = max_pos_con_val;
    else
    {
        if (position_control_output < -max_pos_con_val)
            position_control_output = -max_pos_con_val;
    }

    //introduce offset of 512
    position_control_output += 512;

    P_PWM1.PWDR1.L.BYTE = (unsigned char)(position_control_output & 0x00FF);
    //Write to lower 8 bits
P_PWM1.PWDRU1.BYTE = (unsigned char)((position_control_output & 0xFF00)>>8); //Write to upper 2 bits

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

//----------------------------------------------------------
#include <machine.h>
#include "iodefine.h"

//extern void display_word(unsigned int);
extern int read_encoder(void);
extern void serial_transmit(unsigned int);
extern void speed_control(void);
extern void speed_profile(void);
extern void position_control(void);

extern int encoder_count, position_reference;
extern int temp_encoder_count, temp_position_reference;
extern unsigned int position_control_count;
extern unsigned char start_position_control;

#pragma section IntPRG

// vector 1 Reserved
// vector 2 Reserved
// vector 3 Reserved

// vector 4 IRQ0
__interrupt(vect=4) void INT_IRQ0(void) {/* sleep(); */}

// vector 5 IRQ1
__interrupt(vect=5) void INT_IRQ1(void) {/* sleep(); */}

// vector 6 IRQAEC
__interrupt(vect=6) void INT_IRQAEC(void) {/* sleep(); */}

// vector 7 Reserved
// vector 8 Reserved
/ vector 9 WKP0_7
__interrupt(vect=9) void INT_WKP0_7(void) {/* sleep(); */}

// vector 10 Reserved

// vector 11 Timer A Overflow
__interrupt(vect=11) void INT_TimerA(void) {/* sleep(); */}

// vector 12 Counter Overflow
__interrupt(vect=12) void INT_Counter(void) {/* sleep(); */}

// vector 13 Reserved

// vector 14 Timer FL Overflow
__interrupt(vect=14) void INT_TimerFL(void) {/* sleep(); */}

// vector 15 Timer FH Overflow
__interrupt(vect=15) void INT_TimerFH(void)
{
  //if Timer FH interrupt request flag (IRRTH) is set, clear to 0
  if (P_SYSCR.IRR2.BIT.IRRTFH == 1)
    P_SYSCR.IRR2.BIT.IRRTFH = 0;

  if (P_TMRF.TCSR.BIT.CMFH == 1)
  {
    P_TMRF.TCSR.BIT.CMFH = 0;
    encoder_count = read_encoder();

    if (start_position_control)
    {
      if (position_control_count < 300)
        position_control();
      else
        P_IO.PDR9.BYTE &= 0xDF; //Apply BRAKE_N -> P95
    }
    else
    {
      if (position_reference < 0)
      {
        temp_encoder_count = 0 - encoder_count;
        temp_position_reference = 0 - position_reference;
      }
      else
      {
        temp_encoder_count = encoder_count;
        temp_position_reference = position_reference;
      }

      if (temp_encoder_count > temp_position_reference)
      {
        start_position_control = 1;
      }
    }
  }
}
position_control();
}
else
{
P_IO.PDR9.BYTE ^= 0x02;  //Toggle P91

speed_profile();
speed_control();
P_IO.PDR9.BYTE ^= 0x02;  //Toggle P91
}

display_word(encoder_count);
}

/* sleep(); */

// vector 16 Reserved
// vector 17 Reserved

// vector 18 SCI3
__interrupt(vect=18) void INT_SCI3(void) { /* sleep(); */ }

// vector 19 ADI
__interrupt(vect=19) void INT_ADI(void) { /* sleep(); */ }

// vector 20 Direct Transition
__interrupt(vect=20) void INT_Direct_Transition(void) { /* sleep(); */ }
5. Hardware Schematics
When the actual MCU is used, connectors J1 & J2 (sheet 1) are NOT connected.
6. References

2. Quadrature Decoder/Counter Interface ICs, 2002, Agilent Technologies.
5. DLR1414 4-character 5 × 7 Dot Matrix Alphanumeric Intelligent Display with Memory/Decode/Driver, Infineon Technologies.
## Revision Record

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<th>Rev.</th>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
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<tr>
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</tr>
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