

## Enhancing the Performance of Pedometers Using a Single Accelerometer

by Jim Scarlett

The AN-602 application note examined the use of an Analog Devices, Inc. accelerometer to make a simple but relatively accurate pedometer. However, newer devices have been introduced that allow the use of accelerometers in more cost-sensitive applications. Thus, applications such as pedometers are finding themselves in many consumer devices such as cellular handsets.

Given this trend, a closer examination was made of pedometers using a single accelerometer. The AN-602 technique was implemented in an attempt to duplicate its results. Though the algorithm performed well, the same accuracy was not duplicated. In particular, there was greater variation than expected from person to person, as well as when one person used a different pace and stride length. This led to an investigation of potential improvements to the algorithm used in AN-602.

The tests were done using two different pedometer test boards, both utilizing an ADuC7020 ARM7<sup>®</sup> controller. One setup was a combination of the ADuC7020 microcontroller and ADXL322 accelerometer evaluation boards, with an added 16 × 2 character LCD display. The other was a custom board using the ADuC7020 and an ADXL330 3-axis accelerometer, again with a 16 × 2 character LCD display. See Figure 5 for the custom board schematic.

### AN-602 METHOD

The underlying reasoning in the AN-602 method is based on the principle that the vertical bounce in an individual's step is directly correlated to that person's stride length (see Figure 1).

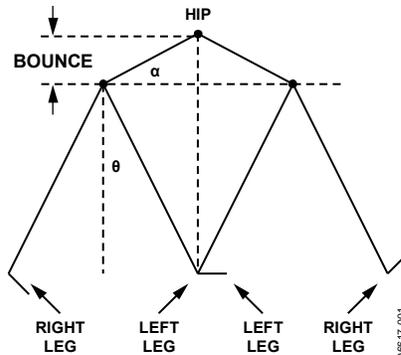


Figure 1. Vertical Movement of Hip While Walking

Because the angles  $\alpha$  and  $\theta$  are equal, the stride can be shown to be a multiple of the maximum vertical displacement. Differences in an individual's leg length are accounted for, given that for the same angles the vertical displacement would be greater or smaller for taller or shorter people.

Using an accelerometer, however, gives changes in acceleration rather than displacement. These acceleration measurements must be converted to a distance before they can be used. With the limited computing power available in the AN-602 setup, a simple formula was used to approximate the double integral needed for the conversion. With plenty of processing power available, an attempt was made to do the discrete integrals directly for this experiment.

A simple method was chosen to calculate the integrals. After each step was determined, all of the acceleration samples within that step were added to obtain a set of velocity samples. The velocity samples for each step were normalized such that the final sample was zero. They were then added together to get a value for the displacement.

This technique looked promising initially, because measured distances were relatively consistent for one subject walking a course multiple times. However, the variance problem from person to person was exacerbated, as was the variance for one subject at different paces. This led to an investigation of whether the problem is with the model itself.

**UNDERSTANDING THE MODEL**

This model has two primary conditions. First, it assumes that the foot actually makes contact with the ground at a single point. Second, it assumes that the impact of each foot on the ground is perfectly elastic. Of course, neither of these is the case. The question arose of whether this can explain the large variations encountered. Based on this experiment, it is safe to state that it does explain much of the variation.

To understand this, it helps to look at the measured acceleration values over several steps, shown in Figure 2. Different sources of spring in one person's step are shown on the data.

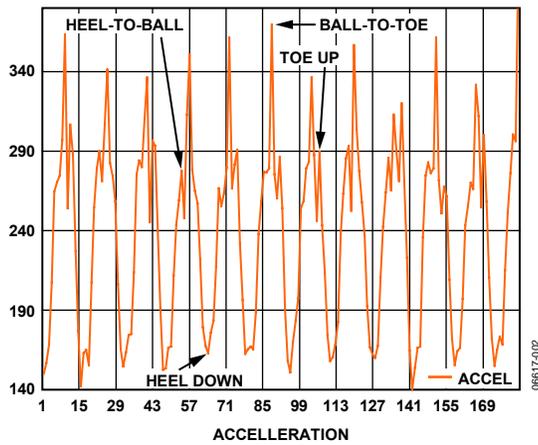


Figure 2. Acceleration Graph for Subject 1 at a Normal Pace

Figure 2 demonstrates the problems encountered trying to translate acceleration measurements into an accurate distance calculation. Methods that take into account the peak-to-peak change (or even those that integrate the data) run into trouble with this type of data. The cause of this difficulty is the variation in spring in the steps of different people, or in the steps of one person using different paces from one measurement to another.

Figure 3 shows the same subject with a longer and faster stride. The peak-to-peak acceleration difference is larger, and the various spring points look different. Thus, the amount of data representing spring data vs. the amount representing real data is different compared with Figure 2. However, the algorithm only sees a set of acceleration measurements and does not note the context of those measurements. The problem, therefore, is how to remove the effect of the spring in a subject's step without removing useful data.

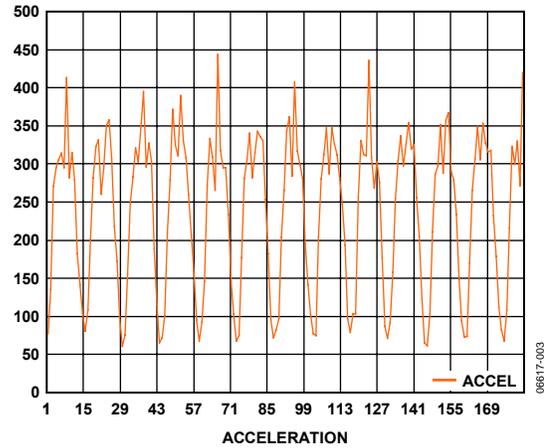


Figure 3. Acceleration Graph for Subject 1 at a Fast Pace

There are some important differences between the two plots. The bottom part of the curve for each step is slightly narrower in Figure 3 and the tops of the curves are more consistent (fewer distinctive peaks). These differences result in a higher average value of the samples compared to the minimum and maximum sample values.

For comparison purposes, review the data plot for a different individual in Figure 4. The stride length is very similar to that of Subject 1 in Figure 2. However, the data itself looks very different.

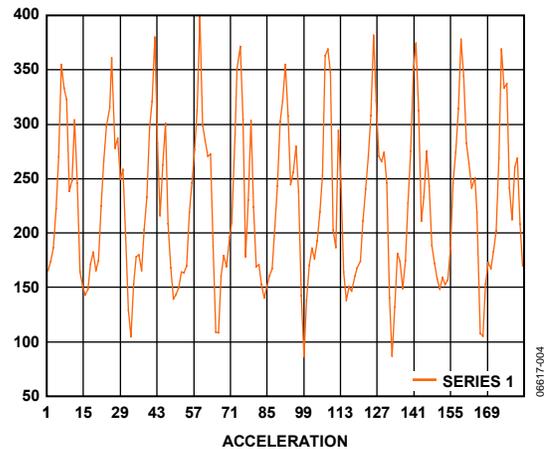


Figure 4. Acceleration Graph for Subject 2 at a Normal Pace

The stride of Subject 2 has a great deal more spring in it than that of Subject 1 (shown in Figure 2). Yet both sets of data represent roughly the same distance walked. Calculating distance solely on the peak values gives widely varying results. Using a simple double integration suffers from the same problem.

## SOLVING THE PROBLEM OF SPRING

All efforts to come up with a decent solution to this problem using straightforward calculations had the same problems. This led to a series of attempts to normalize the data in a way that eliminated the spring, but all these attempts proved unsuccessful. The main reason seemed to be that they required some knowledge of the context of the data. In actual use, however, the system has no idea what is going on outside; all it has are data points. The solution needs to be able to operate on the data without context.

A possible solution to this problem began to emerge. It was noted earlier how the data changed when going from a slower to faster pace. There is less apparent variation due to the spring with a longer, quicker stride. The result was a higher average for the sample points, with respect to the data minima and maxima.

Visually, it is a little difficult to be sure of this, given the amount of bounce in the steps shown in Figure 4. But calculations showed that the average-vs.-peak values are very similar to those in Figure 2. Therefore, a possible simple algorithm was used to determine the distance walked. It is

$$d = k \times \frac{(avg - min)}{(max - min)} \quad (1)$$

where:

$d$  is the distance calculated.

$k$  is a constant multiplier.

$max$  is the maximum acceleration value measured within this step.

$min$  is the minimum acceleration value.

$avg$  is the average acceleration value for the step.

Equation 1 is completed for each step, as determined by a different step-finding algorithm. The step-finding algorithm uses an 8-point moving average to smooth the data. It searches for a maximum peak, followed by a minimum. A step is counted when the moving average crosses the zero point, which is the overall average for the step. The data used in the distance algorithm takes into account the 4-point latency of the moving average.

This simple solution held up well for Subject 1 over various stride lengths. It also did reasonably well with additional subjects. But some subjects produced distances that varied as much as 10% from the average measured distance for the group. This was not within the  $\pm 7.5\%$  error band that was targeted for an uncalibrated measurement. Another solution was needed.

The ratio used in the last test seemed to reflect the differences in the spring of different subjects' steps. It made sense to try combining the two methods examined here. Going back to the original idea of using a double integral, this ratio was used as a correction factor to remove the spring data from the calculation. The resulting formula is therefore

$$d = k \times \sqrt{\frac{(max - min)}{(avg - min)} * \sum \sum (accel - avg)} \quad (2)$$

where  $accel$  represents all measured acceleration values for the step.

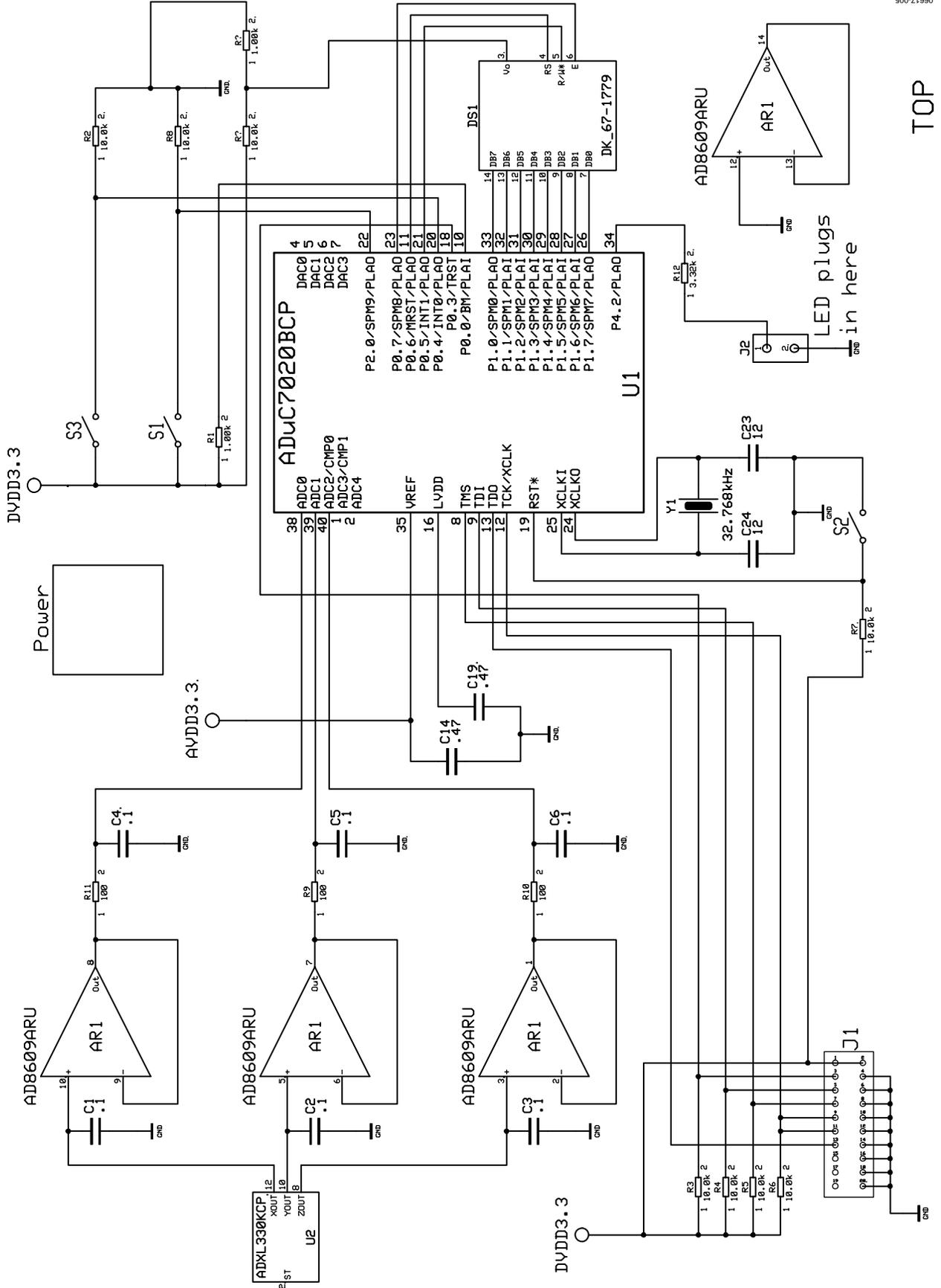
This algorithm held up well for a variety of subjects and paces, with all variation within approximately 6%. The algorithm lends itself to easy calibration for a specific individual/pace by adjusting the Multiplier  $k$ . There is also provision within the listed code to perform an average on the stride length to smooth out step-to-step variation. The results noted here did not include the use of this averaging.

In this experiment, only the X- and Y-axes were used. The 3-axis accelerometer was chosen for flexibility, and two axes were found to be adequate for the task. An ADXL323 could be used in place of the ADXL330. The same layout can be used for both because the pin configuration is identical except for the Z-axis output.

These experiments concentrated on achieving good results for the pedometer's distance measurement. There was no extensive work done on the step-counting algorithm beyond ensuring it works well while walking (and running), with measured steps within 1 to 2 steps of the actual number over hundreds of steps taken. However, it is possible that a simple algorithm can be fooled with nonwalking motions. Improvements can be made in that area, such as the time-window function described in AN-602. The object is to ignore steps that are outside the expected time window, while retaining the ability to adapt when the subject changes pace.

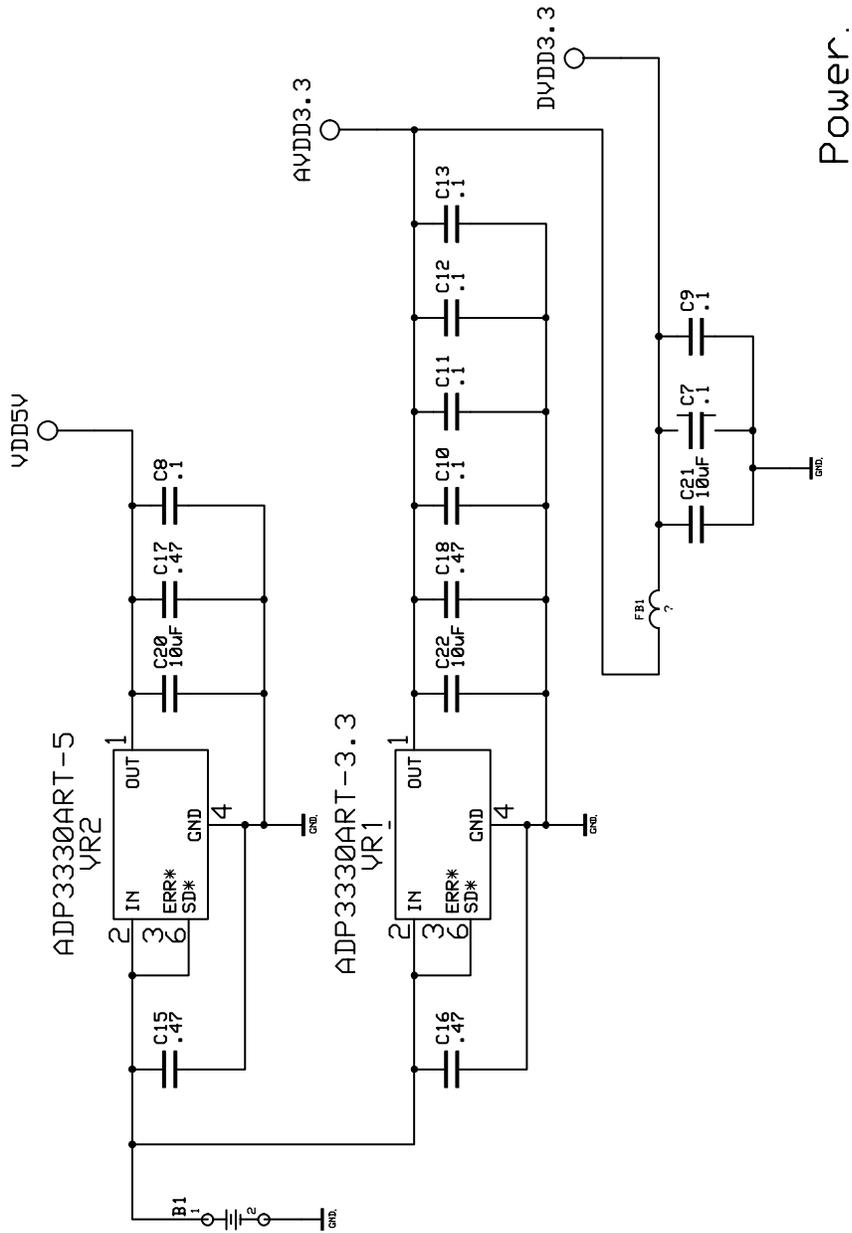
## SUMMARY

This application note represents the results of a single set of experiments attempting to gain decent performance from a simple pedometer that uses a single accelerometer. Some of the barriers to gaining that performance have been reviewed. The final results have met the stated accuracy goals, with the added possibility of improved accuracy with calibration. Although greater accuracy can be obtained with a more complex system (for instance, with multiple accelerometers), the algorithm provided in this application note is an excellent starting point for simple, low cost applications.



TOP

Figure 5. Custom Board Schematic  
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Power.

Figure 6. Custom Board Schematic (Continued)

## ADuC7020 C CODE

The following three files contain the code used to implement this algorithm on the test boards using an ADuC7020 microcontroller.

### MAIN.C

The file *main.c* is used to initialize the device:

```
/******  
Author       : J Scarlett  
Date        : Nov 2006  
Files       : main.c, display.c, ped.c  
Hardware    : ADuC7020  
Description  : Implements a simple pedometer based on application note AN-602  
*****  
*/  
#include <ioaduc7020.h>  
  
//      Function Prototype with required function attribute.  
extern void Monitor_Function(void);  
extern void Display_Init(void);  
  
/******  
// Main Function for ADuC7020 Pedometer essentially performs startup functions  
/******  
int main (void)  
{  
    POWKEY1 = 0x01;  
    POWCON = 0x06;                // set to 653kHz core clock  
    POWKEY2 = 0xF4;  
    REFCON = 0x2;                // use external reference  
                                // (connected to VDD)  
    /******  
    //      Initialize Peripherals  
    /******  
    // GPIO Configuration  
    GP4DAT = 0x04000000;        // P4.2 configured as an output.  
                                // LED is turned on  
    GP0CON = 0x00000000;        //  
    GP0DAT = 0xE0000000;        // 0.7, 0.6, and 0.5 are outputs  
                                // 0.7 = E, 0.5 = R/W*, 0.6 = RS  
    GP1DAT = 0xFF000000;        // All P1 pins are outputs  
  
    ADCCON = 0x20;            // Turn ADC on but do not enable  
  
    Display_Init();           // found in File display.c  
    Monitor_Function();       // found in File ped.c  
    /******  
    // Main Loop  
    /******  
    while(1)  
    {  
    }  
} // main()
```

**DISPLAY.C**

The file *display.c* contains all functions that access the display:

```
// File "display.c"
// performs all LCD display interface functions

#include <ioaduc7020.h>

extern char stepbcd[6];           // found in File ped.c
extern char distbcd[6];          // this too

void Display_Init(void);
void display_data(void);
void display_data_clear(void);
void char_load(int RS, int data);
void delay(unsigned int cycles);
int reverse_data(int data);

void Display_Init()
{
    // used once to initialize display and write
    // the "Steps" and "Distance" headers

    int rs, data;

    // Display initialization
    rs = 0;                               // no RAM access yet

    data = 0x30;                           // function set: 2-line mode, display off
    char_load(rs, data);

    data = 0x38;                           // function set: 2-line mode, display off
    char_load(rs, data);

    data = 0x08;                           // display off, cursor off, blink off
    char_load(rs, data);

    data = 0x01;                           // clear display
    char_load(rs, data);
    delay(49);                             // ~1.5 ms additional delay is required

    data = 0x06;                           // increment mode, no shift
    char_load(rs, data);

    data = 0x0C;                           // display on, cursor off, blink off
    char_load(rs, data);

    data = 0x80;                           // set data address to home, just to be sure
    char_load(rs, data);

    rs = 1;                               // now writing to data RAM
    data = 0x53;                           // start of sequence to send
    char_load(rs, data);                   // "Steps Distance" for title line

    data = 0x74;                           // "t"
```

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```
char_load(rs, data);

data = 0x65; // "e"
char_load(rs, data);

data = 0x70; // "p"
char_load(rs, data);

data = 0x73; // "s"
char_load(rs, data);

data = 0x20; // " " times 3
char_load(rs, data);
char_load(rs, data);
char_load(rs, data);

data = 0x44; // "D"
char_load(rs, data);

data = 0x69; // "i"
char_load(rs, data);

data = 0x73; // "s"
char_load(rs, data);

data = 0x74; // "t"
char_load(rs, data);

data = 0x61; // "a"
char_load(rs, data);

data = 0x6E; // "n"
char_load(rs, data);

data = 0x63; // "c"
char_load(rs, data);

data = 0x65; // "e"
char_load(rs, data);

} // Display_Init()

void display_data()
{
    // displays the data contained in stepbcd[] & distbcd[]
    // beginning at the first and ninth characters
    // on row 2 of the display

    int i, rs, data, zero;

    rs = 0; // want to set address, not data
    data = 0xC0; // start of second line
    char_load(rs, data);
```

```

rs = 1;
zero = 0;
for (i=5; i>=0; i--) // display steps
{
    if ((stepbcd[i] > 0) || (zero ==1)) // suppress leading zeroes,
    { // but not embedded zeroes
        zero = 1;
        data = 0x30 | stepbcd[i]; // numbers on display character table
        char_load (rs, data); // begin at 0x30
    } // if
} // for

rs = 0; // set address
data = 0xC8; // ninth character of second line
char_load(rs, data);

rs = 1;
zero = 0;
for (i=5; i>=0; i--) // display distance
{
    if ((distbcd[i] > 0) || (zero ==1))
    {
        zero = 1;
        data = 0x30 | distbcd[i];
        char_load (rs, data);
    } // if
} // for

} // display_data()

void display_data_clear(void)
{
    // used to clear display data field
    // before new measurement

    int i, rs, data;

    rs = 0; // want to set address
    data = 0xC0; // start of second line
    char_load(rs, data);

    rs = 1;
    data =0x20;
    for (i=0; i<16; i++) // put spaces across Row 2
        char_load (rs, data);

} // display_data_clear()

void char_load(int rs, int data)
{

```

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```
// signal timing assumes a core clock < 4MHz
// delay at end is ~61us, to allow write to complete

data = reverse_data(data); // board layout dictated reversing MSB/LSB
GP1CLR = 0x00FF0000; // ensure clean slate for next character
GP1SET = data << 16; // set Port 1 to new character data

if (rs)
    GP0SET = 0x00400000; // RS bit = 1
else
    GP0CLR = 0x00400000; // RS bit = 0

GP0CLR = 0x00200000; // WR bit = 0 (this is a write command)

GP0SET = 0x00800000; // set E bit to begin transfer process
GP0CLR = 0x00800000; // clear E bit to complete transfer process

delay(2);

} // char_load()

void delay(unsigned int cycles)
{
    T2CON = 0;
    T2CLR = 0;
    T2LD = cycles;
    T2CON = 0xC0; // enable Timer 2, periodic mode, 32.768 kHz
    while (!(IRQSIG & WAKEUP_TIMER_BIT)); // wait for timeout
    T2CON = 0; // disable Timer 2
} // delay()

int reverse_data(int data)
{
    int i, temp;

    temp = 0;

    for (i=0; i<4; i++)
    {
        temp |= (((0x01 << i) & data) << (7 - (2 * i)));
    } // fill top 4 bits of temp

    for (i=4; i<8; i++)
    {
        temp |= (((0x01 << i) & data) >> ((2 * i) - 7));
    } // fill bottom 4 bits of temp

    return temp;
} // reverse_data()
```

**PED.C**

The file *ped.c* contains those functions used by the pedometer algorithm:

```
// file "ped.c"
// performs pedometer and misc functions

#include <ioaduc7020.h>
#include <math.h>
#include <stdlib.h>

//      Function Prototype & variables
char stepbcd[6];
char distbcd[6];
char stepflag;
float stride, avgstride, accel_dat[50];
float maxavg, minavg, accel_avg, velocity, displace;
float distance;
int steps;

void Monitor_Function(void);
void get_sample(unsigned int *xdat, unsigned int *ydat, unsigned int *zdat);
char IsStep(float avg, float oldavg);
void display_prep(void);
long int bin_to_bcd(long int bin_no);
extern void display_data(void);           // found in File display.c
extern void display_data_clear(void);    // found in File display.c

// functions

void Monitor_Function()
{
    char flag;
    unsigned int xdat, ydat, zdat;
    int i, cycle_count, tot_samples, avgconst = 1, latency = 4, avglen = 8;
    float rssdat, newmax, newmin, oldavg, newavg, avgthresh=1.0;
    float walkfudge = 0.0249;

    flag = 0;

    T1CON = 0;           // turn off interval timer and clear any IRQ
    T1CLR1 = 0;

    while (1)
    {
        if (IRQSIG & XIRQ0_BIT)           // XIRQ0 button has been pressed
        {
            while(GP0DAT & 0x00010);      // wait for XIRQ to be low again
            if (!flag)
            {
                T1CON = 0;           // turn off interval timer
                T1CLR1 = 0;          // clear any timer IRQ

                stepflag = 2;
            }
        }
    }
}
```

```

maxavg = -10000.0;
minavg = 10000.0;
newmax = -10000.0;
newmin = 10000.0;
oldavg = 0.0;
newavg = 0.0;
cycle_count = 0;
tot_samples = 0;
steps = 0;
distance = 0.0;
accel_avg = 0.0;
velocity = 0.0;
displace = 0.0;
avgstride = 0.0;

display_data_clear();           // clear old data from display
flag = 1;
T1LD = 1092;                     // ~30 Hz sample rate
T1CON = 0x2C0;                   // 32.768 kHz clock, timer on,
                                // periodic mode
} // if not running, start.
} // look for stop button
if (GP2DAT & 0x01)
{
    while(GP2DAT & 0x01);
    flag = 0;
} // if running, stop

if (((IRQSIG & GP_TIMER_BIT) && (flag)) != 0) // wait for timeout
                                                // and flag
{
    T1CLR1 = 0;
    if (tot_samples > 7) // subtract first sample in sliding boxcar avg
    {
        oldavg = newavg;
        newavg -= accel_dat[cycle_count - avglen];
    } // if

    get_sample(&xdat, &ydat, &zdat); // get data from accelerometer
    xdat -= 8192; // subtract Zero g value
    ydat -= 8192;
    rssidat = sqrt((float)(xdat*xdat + ydat*ydat)/16.0); // vector sum
    accel_dat[cycle_count] = rssidat; // place current sample data in buffer

    newavg += rssidat; // add new sample to sliding boxcar avg
    if((abs(newavg-oldavg)) < avgthresh)
        newavg = oldavg;

    if (rssidat > newmax)
        newmax = rssidat;
    if (rssidat < newmin)
        newmin = rssidat;
}

```

```

tot_samples++;
cycle_count++; // increment count of samples in current step

if (tot_samples > 8)
{
    if (IsStep(newavg, oldavg))
    {
        for (i = latency; i < (cycle_count - latency); i++)
            accel_avg += accel_dat[i];
        accel_avg /= (cycle_count - avglen);

        for (i = latency; i < (cycle_count - latency); i++)
        {
            velocity += (accel_dat[i] - accel_avg);
            displace += velocity;
        } // create integration and double integration

        // calculate stride length
        stride = displace * (newmax - newmin) / (accel_avg - newmin);
        stride = sqrt(abs(stride));

        // use appropriate constant to get stride length
        stride *= walkfudge;

        // generate exponential average of stride length to smooth data
        if (steps < 2)
            avgstride = stride;
        else
            avgstride = ((avgconst-1)*avgstride + stride)/avgconst;

        steps++;
        distance += avgstride;

        // need all data used in calculating newavg
        for (i = 0; i < avglen; i++)
            accel_dat[i] = accel_dat[cycle_count + i - avglen];

        cycle_count = avglen;
        newmax = -10000.0;
        newmin = 10000.0;
        maxavg = -10000.0;
        minavg = 10000.0;
        accel_avg = 0;
        velocity = 0;
        displace = 0;

        display_prep();
        display_data();

        // temporary
        if (GP4DAT & 0x04) // toggle LED to reflect step
            GP4CLR = 0x040000;
        else

```

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```
GP4SET = 0x040000;

    } // we have a new step
} // enough samples to start checking for step (need at least 8)

    } // if timeout
} // continual loop

} // Monitor_Function()

void get_sample(unsigned int *xdat, unsigned int *ydat, unsigned int *zdat)
{
    // gets new samples for x, y, z axes
    // sums together 4 measurments to get average

    int i;

    *xdat = 0;
    *ydat = 0;
    *zdat = 0;

    for (i=0; i<15; i++)
    {
        ADCCP = 0; // x axis
        i++; // delay one command cycle
        ADCCON = 0xA3;
        while (!(ADCSTA));
        *xdat += ((ADCDAT >> 16) & 0xFFF); // data is in bits 16 - 27, so shift is necessary

        ADCCP = 1; // y axis
        i++;
        ADCCON = 0xA3;
        while (!(ADCSTA));
        *ydat += ((ADCDAT >> 16) & 0xFFF);

        ADCCP = 2; // z axis
        i++;
        ADCCON = 0xA3;
        while (!(ADCSTA));
        *zdat += ((ADCDAT >> 16) & 0xFFF);
    } // for
} // get_sample()

char IsStep(float avg, float oldavg)
{
    // this function attempts to determine when a step is complete

    float step_thresh = 5.0; // used to prevent noise from fooling the algorithm

    if (stepflag == 2)
    {
```

```

        if (avg > (oldavg + step_thresh))
            stepflag = 1;
        if (avg < (oldavg - step_thresh))
            stepflag = 0;
        return 0;
} // first time through this function

if (stepflag == 1)
{
    if ((maxavg > minavg) && (avg >
        ((maxavg+minavg)/2)) &&
        (oldavg < ((maxavg+minavg/2))))
        return 1;
    if (avg < (oldavg - step_thresh))
    {
        stepflag = 0;
        if (oldavg > maxavg)
            maxavg = oldavg;
    } // slope has turned down
    return 0;
} // slope has been up

if (stepflag == 0)
{
    if (avg > (oldavg + step_thresh))
    {
        stepflag = 1;
        if (oldavg < minavg)
            minavg = oldavg;
    } // slope has turned up
    return 0;
} // slope has been down

return 0;

} // IsStep()

void display_prep()
{
    int i;
    long int temp;

    // convert steps to BCD values for sending to display
    temp = steps;
    temp = bin_to_bcd(temp); // function to convert binary
    for (i=0; i<6; i++) // to BCD
    {
        stepbcd[i] = (char)(0xF & temp); // load each digit
        temp = temp >> 4;
    } // for

    // convert distance to BCD values for sending to display

```

# AN-900

```
temp = (long int)(distance); // convert float to long int
temp = bin_to_bcd(temp);
for (i=0; i<6; i++)
{
    distbcd[i] = (char)(0xF & temp); // load each digit
    temp = temp >> 4;
} // for

} // display_prep()

long int bin_to_bcd(long int bin_no)
{
    int i;
    long int divisor, multiplier, bcd_no, temp;

    divisor = 100000;
    multiplier = 1048576;
    bcd_no = 0;
    temp = 0;

    if (bin_no > 999999)
        bin_no = 999999;

    for (i=0; i<6; i++)
    {
        temp = bin_no/divisor; // determine each digit starting
        bin_no -= temp*divisor; // with most significant
        temp *= multiplier; // subtract this amt
        bcd_no += temp; // generate hex equivalent
        // put bcd value together

        divisor /= 10; // go to next digit
        multiplier = multiplier >> 4;
    } // for

    return bcd_no;
} // bin_to_bcd()
```