week	lecture	topics
11	Embedded Control Applications III	- Real-time data logger (menu driven, serial communications, adjustable sample rate)

Real-Time Data Logger

- Many applications rely on the timely acquisition of sensory data; the samples have to be taken at a pre-defined sample rate and uploaded to a host computer
- Simple real-time programs rely on *timer interrupts* to ensure that all real-time tasks run in appropriately scheduled time slots; more complex timing issues are commonly solved using real-time operating systems
- A simple real-time data logger can be implemented by reading out the ADC result register from within a timer interrupt service routine; the thus acquired data can be stored or directly uploaded to the host

Real-Time Data Logger

- This lecture will outline the design of such a simple real-time data logger for the C167 microcontroller
- Timer interrupt T0 is used as timing engine; this is one of the fast Capture-Compare timers (maximum resolution: 8 CPU clock cycles $\rightarrow 8/20 \cdot 10^6 = 400$ ns)
- Sample periods from 100 µs to 3.36 s can be chosen – to extend this range, timer T0 would have to be cascaded with another timer (e.g. GPT timer T6)
- The *T0 Interrupt Service Routine* (ISR) is used to read out the ADC unit (channel 0); this data is *time stamped* and stored in a circular buffer

Real-Time Data Logger

- Upon acquisition of the requested number of samples, the entire *data is uploaded to a host computer* via the serial interface ASC0; opening a terminal program (56700 bps, 8/N-1) allows the data to be monitored in tabular format
- As the program will be extended to acquire data straight into the MATLAB workspace, all clear text messages can be switched off using a global *macro MATLAB;* calling the compiler with this macro defined, causes it to ignore all those code sections which would produce these messages

Real-Time Data Logger

- The *serial communication interface* is implemented using *blocking* functions (polling); future extensions could replace these functions by the background communication interface developed in lecture MP7
- A *modular approach* is taken to keep functionally distinct functions in separate source code files; this will greatly facilitate the maintenance and future extensions of the program
- The timing of the real-time engine can be monitored on port 2 pin 0 (P2.0); definition of *macro TIMINIG* causes the compiler to include the relevant code

Real-Time Data Logger

The program consists of the following modules:

- DAC167.c : *main*, global definitions
- serial_poll.c : serial communication interface
- timer.c : timer T0 routines
- start167.a66 : phyCORE-167 startup file

Header files (export public functions and variables)

- DAC167.h : local and global declarations
- serial_poll.h : declaration of serial interface
- timer.h : declaration of timer functions

Real-Time Data Logger: *Main program*

- This is the main module; all global variables are defined here (and exported via the DAC167.h)

```
/*****************************************************************************/
/*      DAC167.C:  Data Acquisition using the C167CR                         */
/*****************************************************************************/

#include <reg167.h>                     /* special function register C167 */
#include <stdio.h>                      /* sscanf() */
#include "DAC167.h"                     /* global project definition file */
#include "serial_poll.h"                /* serial communication routines */
#include "timer.h"                      /* timer functions */

/*
 * global variables (system wide)
 */

unsigned int        stillToRead;        /* number of samples still to be read */
unsigned int        sindex;             /* current 'save index' (save_record) */
unsigned int        savefirst;          /* first 'save index' (circular buffer) */
struct mrec         save_record[SCNT];  /* buffer for measurements */
struct mrec         current;            /* current measurement */
unsigned long int   usSamInt;           /* sample interval in microseconds */
   (…)
```


Real-Time Data Logger: *Main program*

```
   (…)
/*
 * static global variables (file level)
 */

static unsigned int nSample;           /* total number of samples to be acquired */

/* welcome message, static -> global at file level, const -> remains in ROM */
static const char startup_message[] =
   "\n"
   "+*********** REMOTE MEASUREMENT RECORDER using C167 ***********+\n"
   "\n";
   (…)
```

There are truly *global variables* (visible to the other modules) and *static global variables* (only visible within the current source code file)

Variable *startup_message[]* has been defined using the storage class specifier *const;* this causes the associated text to be kept in ROM only

Global variable *save_record[]* and *current* are of type *struct mrec;* this structure has been defined in header file DAC167.h

Real-Time Data Logger: *Main program*

```
   (…)
/* ************************************************************************
 * main program ***********************************************************
 * ************************************************************************/

void main(void) {

  /* toggle LED - allows timing to be verified on P2.1 */
  #ifdef TIMING
  DP2  |= 0x0002;          /* define P2.1 as o/p */
  P2   |= 0x0002;          /* set P2.1 high (inverse logic) */
  #endif

  serial_init();           /* initialize ASC0, 57600 bps, 8/N-1 */
  IEN = 1;                 /* allow all enabled interrupts to be triggered */
   (…)
```

Macro *TIMING* can be set to measure the timing on P2.1: the pin is set low at the beginning of the ISR and reset to high at its end

Upon initializing the serial interface, all *enabled interrupts are allowed*

Real-Time Data Logger: *Main program*

```
   (…)
/* forever... */
  while(1) {

    init_vars();           /* initialize global variables */
    menu();                /* display menu and determine user choice */
    init_T0();             /* initialize timer T0 to the chosen sample rate */

    wait_for_start();      /* blocks until charater 's' is received on ASC0 */
    start_T0();            /* start timer 0 */
    while(stillToRead);    /* 'stillToRead' is decremented by the timer interrupt */

    upload_data();         /* upload data to the host */

  } /* while */
} /* main */
   (…)
```

For improved readability, the *main* program calls upon a number of support functions *(init_vars(), menu(), init_T0*, etc.); *wait_for_start()* waits for character 's' to be sent by the host – this is used as trigger to start data acquisition; once the requested number of samples have been acquired, they are uploaded *(upload_data)*

Real-Time Data Logger: *Support functions*

- The *support functions* keep the code readable:

```
   (…)
/* initialize global variables */
void init_vars(void) {

int idx;                                  /* index for circular buffer */

  /* reset clock record */
  current.time.hour = 0;
  current.time.min = 0;
  current.time.sec = 0;
  current.time.msec = 0;
  current.time.usec = 0;

  /* initialise circular buffer */
  sindex = savefirst = 0;                 /* reset circular buffer index */
  for(idx = 0; idx < SCNT; idx++)         /* mark all records as 'unused' */
     save_record[idx].time.hour = 0xff;   /* (unused flag: hour = 0xff) */

} /* init_vars */
   (…)
```

A slightly wasteful way of *keeping track of the time…*

Real-Time Data Logger: *Support functions*

```
/* determine user choice */
void menu(void) {

char           cmdbuf[15];                /* local command line input buffer */
unsigned int   i;                         /* index for command buffer */

    /* get number of samples and the sampling rate; assume that the format is
       correct (alphanumeric -> to be checked in MATLAB !) */
    #ifndef MATLAB
    myPrintf(startup_message);            /* display startup message */
    myPrintf ("\nEnter number of samples (max: %d): ", SCNT);
    #endif

    getline(&cmdbuf[0], sizeof (cmdbuf));    /* read command line (with echo) */
    for (i = 0; cmdbuf[i] == ' '; i++) { ; } /* skip leading blanks */
    sscanf(cmdbuf, "%d", &nSample);          /* scan input for number of samples */
    if(nSample > SCNT) {
      #ifndef MATLAB
      myPrintf("Too many. Reducing to max. value of %d\n", SCNT);
      #endif
      nSample = SCNT;
    }
```

Support function *menu* reads the number of samples as well as the sample rate from the command line (terminal, connected on ASC0)

Real-Time Data Logger: *Support functions*

```
  (…)
    #ifndef MATLAB
    else myPrintf("Acquiring %d samples\n", nSample);
    #endif

    /* set number of samples that still have to be read (all of'em) */
    stillToRead = nSample;

    /* get sample period in micro-seconds */
    #ifndef MATLAB
    myPrintf ("Enter sample time (microseconds, min. 100): ");
    #endif
    getline(&cmdbuf[0], sizeof (cmdbuf));       /* read command line (with echo) */
    for (i = 0; cmdbuf[i] == ' '; i++) { ; }    /* skip leading blanks */
    sscanf(cmdbuf, "%ld", &usSamInt);           /* scan input for sample rate */
    if(usSamInt < 100) {
      #ifndef MATLAB
      myPrintf("Too fast. Increasing to 100 microseconds (0.1 ms)\n");
      #endif
      usSamInt = 100;                           /* micro-seconds */
    }
    #ifndef MATLAB
    else myPrintf("Sampling interval: %ld microseconds\n", usSamInt);
    #endif

} /* menu */
```


Real-Time Data Logger: *Support functions*

```
/* wait for character 's' to be sent (starts acquisition) */
void wait_for_start(void) {

char myKey;                                     /* start signal: 's' */

    /* issue message */
    #ifndef MATLAB
    myPrintf ("\nPress 's' to start...\n");
    #endif

    /* wait for character 's' */
    while((myKey = _getkey()) != 's');

    /* feedback message */
    #ifndef MATLAB
    myPrintf("Starting data acquisition.\n");
    #endif

} /* wait_for_start */
```

Support function *wait_for_start* calls upon *_getkey()* to receive a character on serial reception line RxD; the function *blocks* as long as this character (once received) is not equal to 's' – this is a simple way of implementing *one-way handshaking*

Real-Time Data Logger: *Support functions*

```
/* display current contents of measurement buffer */
void display_data(struct mrec display) {
unsigned char i;                            /* index count for AN0 - AN3        */

  #ifndef MATLAB
  myPrintf("\rTime: %2d:%02d:%02d.%03d%03d  ",
      display.time.hour, display.time.min,  /* display hours and minutes        */
      display.time.sec, display.time.msec,  /* display seconds and milliseconds */
      display.time.usec);                   /* display microseconds             */

  for (i = 0; i < nCHAN; i++)               /* display AN0 through ANnCHAN      */
    myPrintf(" AN%d : %4.2f V", i, (float)(display.analog[i]) * 5.0 / 1024);
  #else /* MATLAB */
  for (i = 0; i < nCHAN; i++) {
    myPrintf("%d\n", display.analog[i]);    /* display AN0 through ANnCHAN (raw) */
    blinky(1000);                           /* visual feedback during upload */
  }
  #endif /* MATLAB */

} /* display_data */
```

Support function *display_data* displays the contents of a single data record; in *terminal mode*, each record includes a time stamp and the formatted data of the ADC channel(s); in *MATLAB mode*, only raw data values are sent and data the upload is signalled using the LED

Real-Time Data Logger: *Support functions*

```
/* upload data to the host */
void upload_data(void) {

int idx;                                    /* index for circular buffer */

    /* upload data */
    idx = sindex - nSample;                 /* starting index */
    if (idx < 0) idx += SCNT;               /* wrap circular buffer */
    while (idx != sindex) {
       if (save_record[idx].time.hour != 0xff) {
          display_data(save_record[idx]);   /* display record */
       }
       if (++idx == SCNT) idx = 0;          /* next circular buffer entry  */
    } /* while */

} /* upload_data */
```

Support function *upload_data* calls upon *display_data* to send formatted (or raw – MATLAB mode) data records to the host; the function simply loops through all of the currently stored records – memory *save_record* is made circular by resetting the index variable *idx* to '0' when moving beyond the end of the buffer

Real-Time Data Logger: *Timing*

- The heart of the data logger is the timer ISR:

```
static void timer0_ISR(void) interrupt 0x20 using INTREGS {

unsigned int i;

  #ifdef TIMING
  P2  &= ~0x0002;   // clear bit on entry (inverse output logic)
  #endif

  /* update current time */
  current.time.usec += usSamInt;
   (…)
```

Definition of macro *TIMING* allows precise timing information to be produced: upon entry to the ISR, bit 1 of port 2 (P2.1) is set *low*; this bit is reset to *high* before exiting from the ISR

The *micro-second counter* of variable *current* is increased by the per-interrupt increment *usSamInt* and all other counters are adjusted, if required;

Real-Time Data Logger: *Timing*

```
   (…)
while(current.time.usec >= 1000) {
    current.time.usec -= 1000;
    if(++current.time.msec == 1000) {
       current.time.msec = 0;
       if(++current.time.sec == 60) {
          current.time.sec = 0;
          if(++current.time.min == 60) {
             current.time.min = 0;
             if(++current.time.hour == 24)
                current.time.hour = 0;
             }
          }
       }
    }

    /* perform measurement, loop through 'nCHAN' channels... */
    for(i = 0; i < nCHAN; i++) {
       ADCON = i;      /* single channel, single shot conversion, channel 'i' */
       ADST = 1;       /* start conversion */
       while(ADBSY);  /* wait */

       current.analog[i] = ADDAT & 0x03FF;   /* store result */
    } /* for */
```

This is where the actual measurements are taken (one per channel)

Real-Time Data Logger: *Timing*

```
   (…)
    /* store current measurement */
    save_record[sindex++] = current;            /* copy current measurements   */
    if(sindex == SCNT) sindex = 0;              /* check bounds of sindex      */
    if(sindex == savefirst)                     /* check circular buffer limits*/
       if(++savefirst == SCNT)  savefirst = 0;  /* check bounds of savefirst   */

    if(--stillToRead == 0) T01CON = 0x00;       /* stop timer 0 if sRead = 0 */

    #ifdef TIMING
    P2  |= 0x0002;                  /* set bit on exit (inverse output logic) */
    #endif

} /* timer0_ISR */
```

Upon having acquired all selected channels, the *current* measurement is stored in the ring buffer and all index variables are updated; if the store index *(sindex)* exceeds the buffer maximum *(SCNT)* it is reset to '0'

Once the requested number of samples have been taken (variable *stillToRead* is '0') *timer T0 stops itself*

Real-Time Data Logger: *Timing*

- The period of the timer is set by *init_T0:*

```
/* initialize timer T0 */
void init_T0(void) {

unsigned long int period;           /* determine prescale value (T0I) */
unsigned int      T0I;
unsigned int      RLvalue;          /* reload value */

   /* calculate reload value */
   period = 26250;                  /* prescaler 8 (000) */
   T0I = 0;                         /* 000 */

   /* determine suitable period */
   while(usSamInt > period) {
      period *= 2;
      T0I++;                        /* corresponding T0I */
   }
   (…)
```

Function *init_T0* first determines the required pre-scale value *(T0I)* by successively doubling the period, beginning with its minimum value 26250 µs (26.25 ms) until *period* exceeds the requested sample interval

Real-Time Data Logger: *Timing*

```
  (…)
   /* set reload value and program T0I */
   RLvalue = (unsigned int)(0xFFFF*(1 - (float)(usSamInt)/period));
   T0REL = RLvalue;
   T0    = RLvalue;
   T01CON |= T0I;

   /* setup the timer 0 interrupt */
   T0IC  = 0x44;                    /* set T0IE and ILVL = 1, GLVL = 0 */

} /* init_T0 */


/* start timer T0 */
void start_T0(void) {

    T01CON |= 0x0040;

} /* start_T0 */
```

Function *init_T0* then programs the reload value *(RLvalue)* and the interrupt level for timer T0 (ILVL : 1, GLVL : 0)

Function *start_T0* has been provided to start the timer from within higher level functions (main)

Real-Time Data Logger: *Serial interface*

- The serial communication routines have been extended by *getline* and *myPrintf:*

```
#define CNTLQ      0x11
#define CNTLS      0x13
#define DEL        0x7F
#define BACKSPACE  0x08
#define CR         0x0D
#define LF         0x0A

void getline (char near *line, unsigned char n)  {
unsigned char cnt = 0;
char c;

  do  {
    if ((c = _getkey ()) == CR)  c = LF;    /* read character               */
   (…)
```

Function *getline* reads from the serial interface ASC0 until a *carriage return (CR)* character is received; this character is replaced by a *line feed (LF)* to mark the end of string

Real-Time Data Logger: *Serial interface*

```
   (…)
    if (c == BACKSPACE  ||  c == DEL)  {    /* process backspace            */
      if (cnt != 0)  {
        cnt--;                              /* decrement count              */
        line--;                             /* and line pointer             */
        putchar (0x08);                     /* echo backspace               */
        putchar (' ');
        putchar (0x08);
      }
    }
    else if (c != CNTLQ && c != CNTLS)  {   /* ignore Control S/Q           */
      putchar (*line = c);                  /* echo and store character     */
      line++;                               /* increment line pointer       */
      cnt++;                                /* and count                    */
    }
  }  while (cnt < n - 1  &&  c != LF);      /* check limit and line feed    */
  *line = 0;                                /* mark end of string           */
}
```

A check is performed if the received character is a *backspace* or *delete character;* if so, count variable *cnt* is decremented and the latest character on the terminal screen is *overwritten with a blank character*

Printable characters are echoed back to the terminal and stored in the buffer *(line)*

Real-Time Data Logger: *Serial interface*

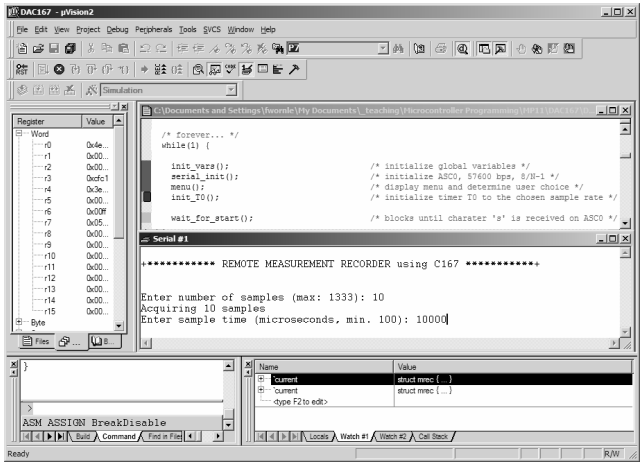
```
/* print formatted through S0 */

#define STRING_BUF 300                      /* size of local buffer for strings */
static char userbuf[STRING_BUF];            /* static -> local to this file */

void myPrintf(char *fmt, ...) {
va_list arg_ptr;

  va_start(arg_ptr, fmt);                   /* fmt : format string */
  vsprintf(userbuf, fmt, arg_ptr);          /* vsprintf accepts ptr to args... */
  va_end(arg_ptr);

  putline(userbuf);

} /* myPrintf */
```

Function *myPrintf* simply extracts the always present format string *(fmt)* and a pointer to an optional list of further parameters *(arg_ptr)* before calling *vsprintf*, the version of *sprintf* which accepts a variable number of call-up parameters

This allows for calls to myPrintf with and without a list of variable parameters: *myPrintf("hello\n");* and *myPrintf("%d\n", myInt);*

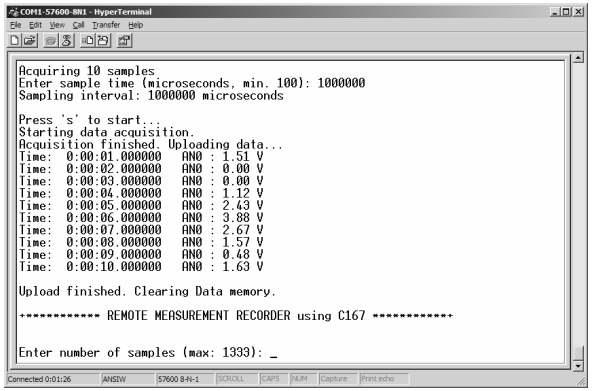
Real-Time Data Logger

Simulation allows validation of the code; *the timing, however, can only be checked on the actual hardware*



Real-Time Data Logger

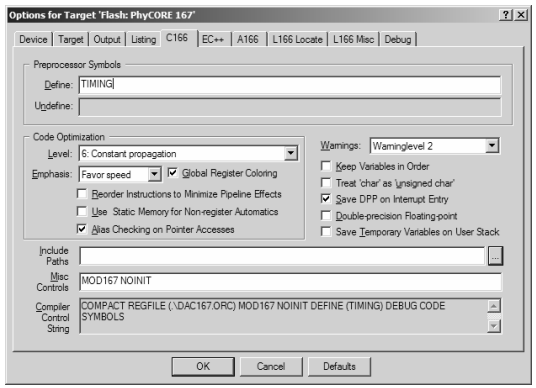
- Upon download to the Flash EEPROM of the target, the code can be controlled using a terminal program:



Real-Time Data Logger

- The requested timing can be checked by checking the voltage on port 2, pin 0 with an *oscilloscope*

- The display of timing information on P2.0 can be enabled using compiler *macro TIMING*

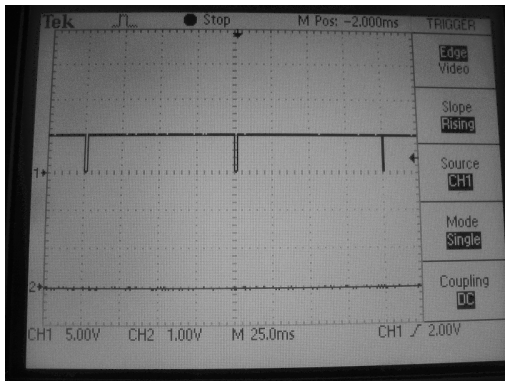


Real-Time Data Logger

- Example: Acquisition of 100 values from ADC channel 0, sample period: 100000 µs = 100 ms

- T0_ISR is called every 100 ms (4 divs at 25 ms / div)

- Duration of the recording: 100·100 ms = 10 seconds

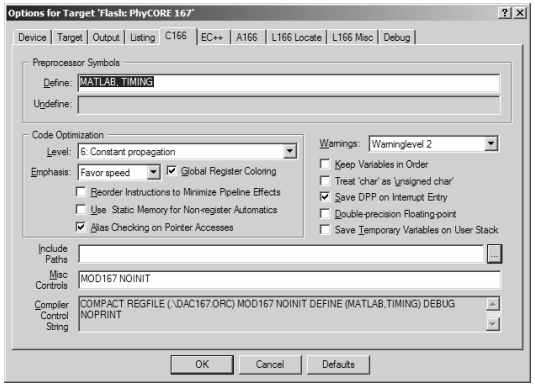


Real-Time Data Logger: *MATLAB interface*

- With minor modifications, the data logger program can be used from within MATLAB – this way data can be *read directly into the MATLAB workspace* where it can be analysed and/or processed
- In its present form, the logger first acquires all requested samples and then uploads them to the host; an improvement would be to use the *background communication routines* developed in lecture MP7 – this way, 'live' data could be visualized
- Here, we shall restrict ourselves to the *sequential* version, i. e. the upload *follows* the acquisition phase

Real-Time Data Logger: *MATLAB interface*

- The upload of unnecessary information (messages, formatted output, etc.) should be suppressed
- Messages can be suppressed by enabling compiler *macro MATLAB;* all macros need to be separated by commas



Real-Time Data Logger: *MATLAB interface*

- A host-sided communication program can easily be written in form of a *MATLAB m-file:*

```
% communicate with uC application DAC167 on the PhyCORE-167
% fw-01-05

% construct serial port object
myBuffer = 1000;
sp_ID = serial('COM1', 'BaudRate', 57600, …
               'InputBufferSize', myBuffer, 'Timeout', 3600);

% open serial port
fopen(sp_ID);
   (…)
```

MATLAB has built-in commands which open/administer/close a *serial port object;* command *serial* accepts a number of parameters which define the characteristics of the port

To *open, write to, read from* and *close* a serial port, MATLAB provides commands *fopen, fwrite/fprintf, fread/fscanf* and *fclose,* respectively.

Real-Time Data Logger: *MATLAB interface*

```
   (…)
while(1)
    % start measurment sequence
    nSamples = input('Number of samples: ');
    Period = input('Sample period (in micro-seconds): ');

    % send nSamples and Period to the target
    fprintf(sp_ID, '%d\n', nSamples);
    dummy = fscanf(sp_ID, '%s');
    fprintf(sp_ID, '%d\n', Period);
    dummy = fscanf(sp_ID, '%s');

    % start execution
    fprintf(sp_ID, '%c', 's');
   (…)
```

The data logger on the C167 initially expects the number of samples *(nSamples)* to be sent, followed by the sample period in micro-seconds *(period);* the data logger echoes all received characters back to the host – the m-file therefore has to read/remove this data from the reception buffer, even if this information is not used *(dummy call to fscanf)*

Data acquisition is initiated by *sending character 's'*

Real-Time Data Logger: *MATLAB interface*

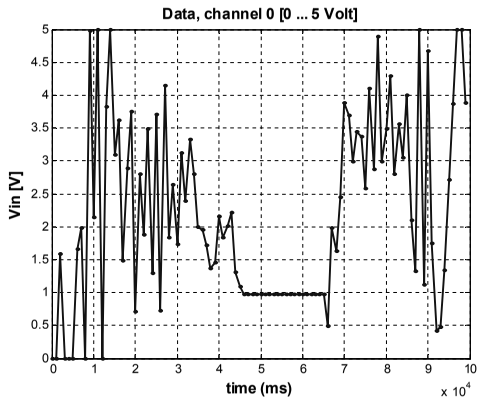
```
    (…)
     % receive data values
     myData = zeros(nSamples, 1);
     for(i = 1:nSamples)
         myVal = fscanf(sp_ID, '%s');
         myData(i) = str2num(myVal)/1023*5;
     end

     % plot results
     t = Period*1e-3*[0:nSamples-1];
     plot(t, myData, 'g.-')
     title('Data, channel 0 [0 ... 5 Volt]');
     xlabel('time (ms)');
     ylabel('Vin [V]');
end

% To disconnect the serial port object from the serial port (- never reached)
fclose(sp_ID);
```

On completion of the data acquisition phase, the logger uploads all data values in its raw 2-byte format; the *values arrive as 'text'* – the m-file therefore has to *convert from strings to numbers*

The re-scaled data values are displayed using the *'plot'* command

Real-Time Data Logger: *MATLAB interface*

- Plotting the acquired data in MATLAB:

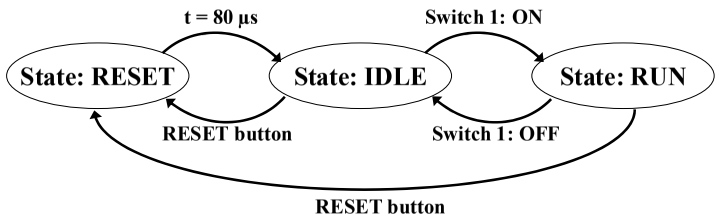


Embedded Control Applications – Outlook

- The presented program is just a *quick'n'dirty* example of a host-target interface; more serious applications should *consider transmission errors* and implement a *protocol with handshaking*
- Transmission errors may lead to situations in which either of the two communication partners expects a signal which will never arrive; this pitfall can be avoided with the use of *timeout timers* (on both sides!) – the design of a robust communication system is not straight forward and is best done using *state diagrams*

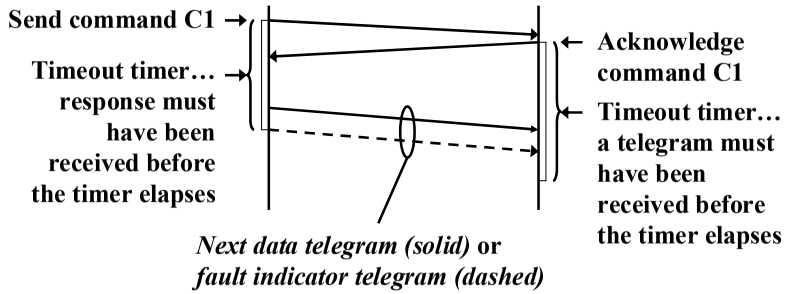
Embedded Control Applications – Outlook

- *State diagrams* help a software designer to visualize the sequence a program runs through in the presence and/or absence of *internal* and *external signals*
- Example: *(generic microcontroller program)*



Embedded Control Applications – Outlook

- The design of a *communication system* often makes use of *telegram sequence diagrams* to visualize the flow of telegrams between the individual partners



Embedded Control Applications – Outlook

- Microcontroller based software almost always benefits from a clear and modular structure; the use of state diagrams greatly assists the programmer in developing such a structure
- The ever increasing complexity of embedded systems has led to a number of formal approaches to software development, e.g. the *Universal Modelling Language (UML)* and corresponding software engineering tools
- *Embedded software engineering* has become so complex that entire degrees focus on nothing else…

Embedded Control Applications – Outlook

- Modern software engineering – a world of its own