EECS 192: Mechatronics Design Lab

Discussion 11: Embedded Software

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8 & 9 April 2015 (Week 11)

- Multitasking Models
- Software Engineering
- Convenience vs. Performance

Multitasking Models

Motivation

Good cars need simultaneous velocity and steering control

- Velocity control needs to time encoder transitions and set motor PWM
- Steering control needs to wait for camera integration, detect line, and update servo
- Also want to stream telemetry data

Cooperative Multitasking: Example

A simple way to achieve multitasking with an event loop:

```
void main() {
  while (1) {
    if (Camera.is_integration_finished()) {
      Servo.set_steering(Camera.detect_line());
      Camera.restart_integration();
    }
    if (Encoder.is_transition()) {
      SpeedSensor.update(Encoder.get_last_width());
      Motor.set_pwm(TARGET_SPEED - SpeedSensor.get());
    }
    Telemetry.do_io();
  }
}
```

What are some issues? Especially related to timing and correctness?

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What are some issues? Especially related to timing and correctness?

- If camera line detection is too long, may miss encoder transitions
  - Even non-critical telemetry can block critical control operations
- Complex, interleaved control structures hinder readability

Interrupts

So I need some way to ensure critical events aren't missed: Interrupts!

- Hardware functionality which interrupts the CPU on some event (like input transition)
- Saves current position in code, then jumps to the ISR (interrupt service routine)
- Once ISR returns, restore previous position in code and continue executing

Interrupts: Example

Let's handle encoders with an interrupt!

```
void encoder_isr() {
  speed = calculate_speed(EncoderTimer.read_us());
  EncoderTimer.reset();
}
void main() {
  EncoderInterrupt.fall(encoder_isr);
  while (1) {
    wait(CAMERA_INTEGRATION_TIME);
    Servo.set_steering(Camera.detect_line());
    Motor.set_pwm(TARGET_SPEED - speed);
    Telemetry.do_io();
  }
}
```

What did we gain?

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    Telemetry.do_io();
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}
```

What did we gain?

- Simpler control logic: camera is just integrate-wait-read
- All encoder transitions recorded, even if faster than camera reads

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```

What new issues did we cause?

- Motor controller frequency tied to camera
- `encoder_isr` can fire anytime/anywhere, even interfering with `main`
  - Really bad things can happen if `encoder_isr` is slow
- Potential race conditions with shared variables (like `speed`)

Threading

What if I want to decouple the motor control loop from the camera control loop?

Threads: sequences of instructions managed independently by a scheduler

- Conceptually runs in parallel, but actually time-multiplexed onto CPU
- Threads regularly pre-empted: paused so another thread can run
  - Called a context switch

Threading: Example

Rewriting the same code with threads:

```
void encoder_isr(); // same as previously
void camera_loop() {  // in a while(1) {...} in own thread
  wait(CAMERA_INTEGRATION_TIME);
  Servo.set_steering(Camera.detect_line());
}
void motor_loop() {  // in a while(1) {...} in own thread
  Motor.set_pwm(TARGET_SPEED - SpeedSensor.get());
  wait(MOTOR_UPDATE_TIME);
}
void telemetry_loop() {  // in a while(1) {...} in own thread
  Telemetry.do_io();
}
```

What got better?

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```

What got better?

- Code is much cleaner: steering and motor control independent
- Motor update rate independent of camera integration time

Threading: Example

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What issues arise?

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}
```

What issues arise?

- Threads can be pre-empted anywhere, even during camera read
- Thread timing granularity can cause integration time inaccuracy
- Scheduling overhead: context switches take time
- Data sharing could be more complicated, requiring synchronization

Benchmarking

But just how bad are those issues?
More importantly, how can we tell?

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More importantly, how can we tell?

Benchmark time, of course!

- Want to determine context switch overhead and schedule frequency
- Strategy
  - Instantiate some threads
  - Each rapidly toggles IO, indicating running
  - View each thread's IO on scope

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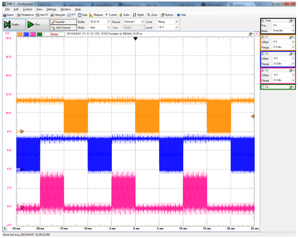
- Strategy
  - Instantiate some threads
  - Each rapidly toggles IO, indicating running
  - View each thread's IO on scope

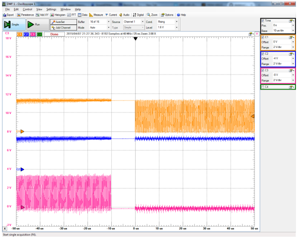
Results:

- Scheduler invocation every 5ms
- Context switch overhead is about 10us

So, this could really mess with integration time.



measure frequency: 5 ms/div



measure overhead: 10 us/div

Better Camera Timing

A simple solution to meet realtime constraints is to change priorities:

```
void camera_thread_fn() {
  while(1) {
    wait(CAMERA_INTEGRATION_TIME);
    Servo.set_steering(Camera.detect_line());
  }
}
void main() {
  ...
  Thread camera_thread(camera_thread_fn);
  camera_thread.set_priority(osPriorityHigh);
  ...
}
```

Why won't this work?

Better Camera Timing

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void camera_thread_fn() {
  while(1) {
    wait(CAMERA_INTEGRATION_TIME);
    Servo.set_steering(Camera.detect_line());
  }
}
void main() {
  ...
  Thread camera_thread(camera_thread_fn);
  camera_thread.set_priority(osPriorityHigh);
  ...
}
```

Why won't this work?

- `wait` is a dumb spin loop, won't yield control to lower priority threads
  - Since `camera_thread_fn` never sleeps, other threads "starve"
  - Instead, use `Thread::wait` to yield to other threads

Misc mbed RTOS topics

- Tickers regularly calls functions using ISRs
  - Standard ISR caveats apply
- RtosTimer can also regularly call functions
  - All timers are handled in a single thread, `osTimerThread`
- The default max number of threads is 6
  - `OS_TASKCNT` and other constants in `mbed-rtos/rtx/RTX_Conf_CM.c`

See the mbed RTOS documentation:

`https://developer.mbed.org/handbook/RTOS`

Software Engineering

Oh Dear...

Can you **easily** tell what this code does?

```
// in main() loop
si = 1; si = 0;
uint16_t data[128];
for (int i=0; i<128; i++) {
  clk = 0;  clk = 1;
  data[i] = ain.read_u16();
}
uint16_t max = 0; uint8_t pos = 0;
for (int i=0; i<128; i++) {
  if (data[i] > max) {
    max = data[i]; pos = i;
  }
}
servo.write(0.075 + 0.025 * (64.0 - pos) / 64);
```

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  if (data[i] > max) {
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  }
}
servo.write(0.075 + 0.025 * (64.0 - pos) / 64);
```

Probably not.

Oh Dear...

Is this better? Why?

```
const uint8_t CAMERA_LENGTH = 128, CAMERA_HALF = CAMERA_LENGTH / 2;
void camera_read(uint16_t* data_out) {
  si = 0; si = 0;
  for (int i=0; i<CAMERA_LENGTH; i++) {
    clk = 0;  clk = 1;
    data_out[i] = ain.read_u16();
  }
}
uint8_t line_detect(uint16_t* cam_data) {
  uint16_t max = 0; uint8_t pos = 0;
  for (int i=0; i<CAMERA_LENGTH; i++) {
    if (cam_data[i] > max) {
      max = cam_data[i]; pos = i;
    }
  }
  return pos;
}
void set_steering_pct(float pct) {
  servo.write(0.075 + 0.025 * (pct));
}

// in main() loop
uint16_t cam_data[CAMERA_LENGTH];
camera_read(cam_data);
int8_t line_offset = CAMERA_HALF - line_detect(cam_data);
set_steering_pct((float)line_offset/CAMERA_HALF);
```

Good Programming Style

Good style produces readable and maintainable code, saving you time later

- Short functions, single responsibility
  - Make it easy to understand
- Consistent level of abstraction
  - Separate the “what” from the “how”
- Don’t repeat yourself (DRY)
  - Copypaste code is bad: making consistent changes becomes very hard

Want to know more? Take cs169!

The Old Fashioned Way

Here's a really basic lost line algorithm:

```
uint16_t last_line_pos = 0;
motor.set_pwm(0.7);
while(1) {
  int16_t line_pos = line_detect(camera_data);
  if (line_pos != -1) { // line detected - follow it
    set_steering_pct(pid_update(line_pos));
  } else { // line not found - rail servo in previous direction
    if (last_line_pos < 64) {
      set_steering_pct(0.0);
    } else {
      set_steering_pct(1.0);
    }
    motor.set_pwm(0.4); // slow down
  }
  last_line_pos = line_pos;
}
```

Is it correct?

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    }
    motor.set_pwm(0.4); // slow down
  }
  last_line_pos = line_pos;
}
```

Is it correct? Nope

- `last_line_pos` immediately clobbered, but not obvious at-a-glance
- Implicit state in motor PWM - forget to reset motor to full speed

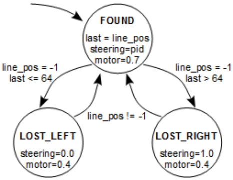
With State Machines

Let's make things clearer by following the state machine model

Write the transition function

```
enum State { FOUND, LOST_LEFT, LOST_RIGHT };

State do_transition(State current_state, int16_t line_pos
    , int16_t last) {
  if (current_state == FOUND) {
    if (line_pos == -1) {
      if (last <= 64) {
        return LOST_LEFT;
      } else {
        return LOST_RIGHT;
      }
    }
  } else {
    if (line_pos != -1) {
      return FOUND;
    }
  }
}
```



lost track state machine graphical notation

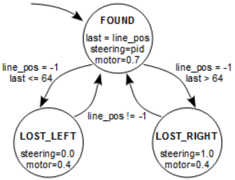
With State Machines

Let's make things clearer by following the state machine model

Write the state actions

```
enum State { FOUND, LOST_LEFT, LOST_RIGHT };

void state_action(State state, int16_t line_pos, int16_t&
      last) {
  if (state == FOUND) {
    set_steering_pct(pid_update(line_pos));
    set_motor_pwm(0.7);
    last = line_pos;
  } else if (state == LOST_LEFT) {
    set_steering_pct(0.0);
    set_motor_pwm(0.4);
  } else if (state == LOST_RIGHT) {
    set_steering_pct(1.0);
    set_motor_pwm(0.4);
  }
}
```



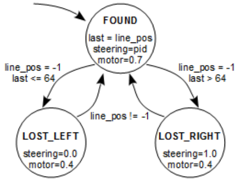
lost track state machine graphical notation

With State Machines

Let's make things clearer by following the state machine model

... and put it all together

```
int16_t last = 0;
State state = FOUND;
while (1) {
  int16_t line_pos = line_detect(camera_data);
  state = do_transition(state, line_pos, last);
  state_action(state, line_pos, last);
}
```



lost track state machine graphical notation

Convenience vs. Performance

DigitalOutput

Given this simple block of code, guess the waveform frequency...

```
DigitalOut wave(PTB2);
while(1) {
  wave = !wave;
}
```

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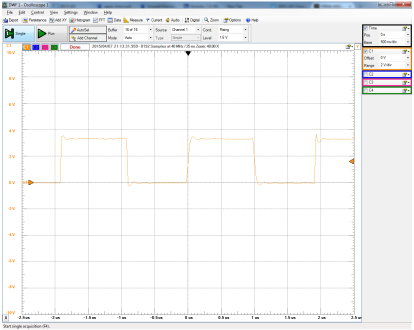


About 0.5MHz!
(or 1 edge per us)
That's at least an order of magnitude slower than the instruction clock!

Where might the bottleneck be?

Under the Hood: How DigitalOut Works

mbed/api/DigitalOut.h

```
class DigitalOut {
    void write(int value) {
        gpio_write(&gpio, value);
    }
}
```

mbed/targets/hal/TARGET_Freescale/TARGET_KLXX/gpio_object.h

```
typedef struct {
    PinName  pin;
    uint32_t mask;
    __IO uint32_t *reg_dir;
    __IO uint32_t *reg_set;
    __IO uint32_t *reg_clr;
    __I  uint32_t *reg_in;
} gpio_t;

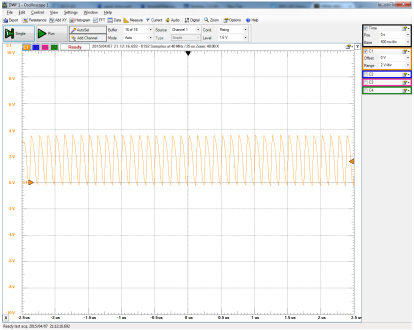
static inline void gpio_write(gpio_t *obj, int value) {
    if (value)
        *obj->reg_set = obj->mask;
    else
        *obj->reg_clr = obj->mask;
}
```

Many levels of indirection for a simple register write!

Raw register access

What if we skip the mbed API and directly write the register?

```
DigitalOut wave(PTB2); // set pin as output
while(1) {
  PTB->PTOR = (0x01 << 2); // set toggle register to flip pin PTB2
}
```



Much faster: about 8MHz!
(or 16 edges per us)

Each GPIO port has these registers:

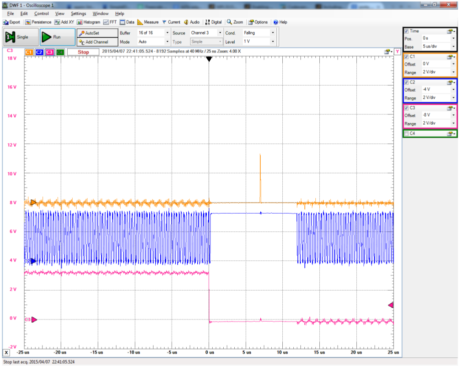
PDOR: set data
PSOR: set bits
PCOR: clear bits
PTOR: toggle bits
PDIR: input
PDDR: directionality

See MKL25Z4.h for details

InterruptIn Latency

Similarly, let's measure the InterruptIn latency

- ch1 (yellow) spike is ISR body
- ch2 (blue) toggling is main loop
- ch3 (pink) is interrupt signal
- Interrupts enabled using InterruptIn.fall(...)

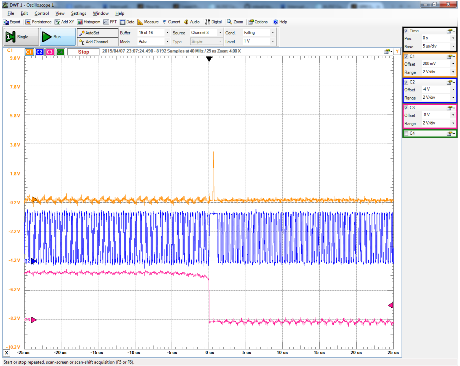


About 7us from edge to interrupt

InterruptIn Latency

What about a lower level implementation?

```
extern "C" void PORTA_IRQHandler() {
  PTB->PTOR = 0x04; PTB->PTOR = 0x04; // toggle ch1 (yellow)
  PORTA->ISFR = PORT_ISFR_ISF_MASK; // clear interrupt flags
}
NVIC_SetVector(PORTA_IRQn, (uint32_t)PORTA_IRQHandler); // set interrupt handler function
PORTA->PCR[16] = (PORTA->PCR[16] | PORT_PCR_IRQC_MASK); // enable on PTC16 / ch3 (pink)
NVIC_EnableIRQ(PORTA_IRQn);
```



Much faster: about 0.5us from edge to interrupt

But does this really matter?

- Order of magnitude faster
- ... but it's still microseconds
- Unlikely to be a bottleneck

Summary

- Interrupts and threading can make multitasking easier
  - Also come with their set of pitfalls and issues
- Write good code so you don't hate yourself later
- If you have high performance requirements, go below the mbed API
  - But in absolute timing terms, unlikely to make a significant difference

- Questions? Feedback?