CDS 270-2: Lecture 2-1
Multi-Threaded Control Systems

Richard M. Murray

3 April 2006

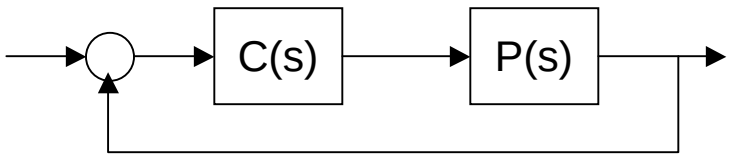
Goals:

- Describe multi-threaded execution in the context of control systems
- Introduce *Pthreads*, a standard library for multi-threaded programming

Reading:

- "POSIX Threads Programming", Lawrence Livermore National Laboratory. 2006 (online tutorial)
- "Monitors: An Operating System Structuring Concept", C. A. R. Hoare. Communciations of the ACM, 17(10):549--557, 1974.

Traditional Control Systems Implementation (Sparrow)



$$C(s) \xrightarrow{\text{Tustin}} C(z)$$

Simplest case: interrupt driven loop

- Use HW/SW interrupts to run control routine at an accurate and fixed rate
- "Servo loop" overrides normal program operation
- Need to be careful about interaction of variables in servo loop with main pgm

Variations:

- Time-triggered protocols - scheduling of events to allow multiple "servos"

Sample program

- Discrete time implementation

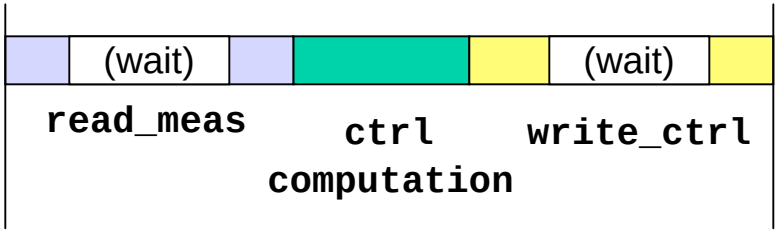
$$z_{k+1} = A_c z_k + B_c e$$
$$y_k = C_c z_k + D_c e$$

- Uses quasi-sparrow implementation

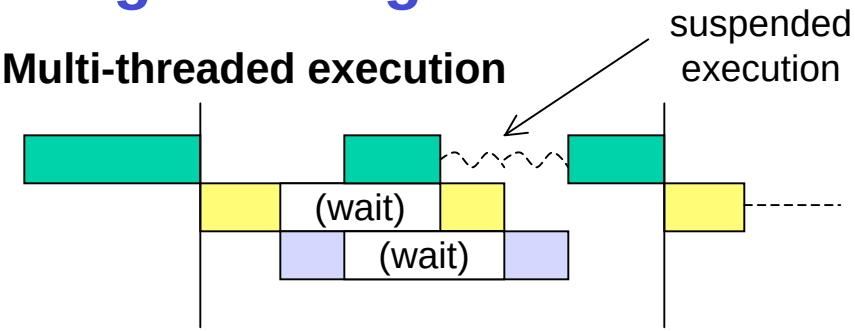
```
load_controller(file)
servo_setup(loop, rate, flags);
servo_enable();

loop()
{
  y = read_measurement();
  r = read_reference();
  xnew = Ac * x + Bc * (r – y);
  u = Cc * x + Dc * (r – y);
  write_control(u);

  x = xnew;
}
```

Multi-Threaded Programming

Single threaded execution



Multi-threaded execution



Basic Idea

- Separate code into independent segments (“threads”)
- Switch between threads, allowing each to run “simultaneously”
- Threads share memory and devices; allows rapid sharing of information

Advantages

- Avoid manual coding to eliminate pauses due to hardware response
- Multiple control loops become separate threads; OS insures execution
- Allows messages (or signals) to be received in middle of long computation

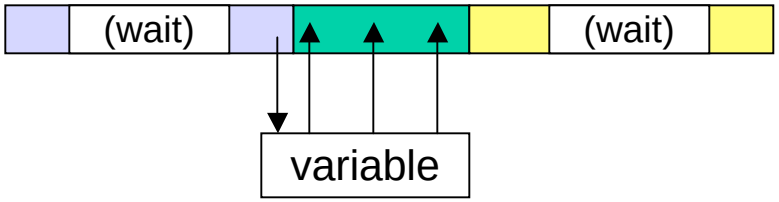
Threads vs Processes

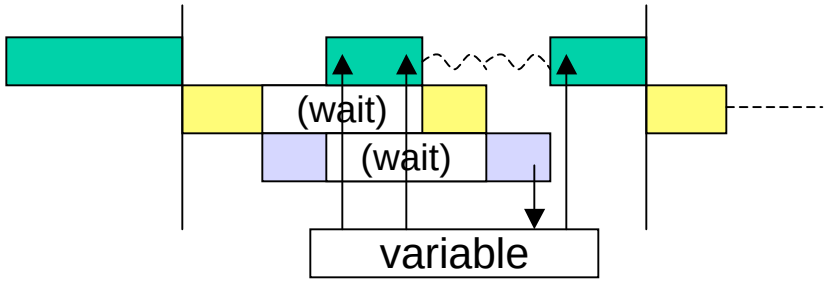
- Processes have separate memory space and device handles
- Requires interprocess communication to share data

Issues

- Race conditions
- Dead locks (“deadly embrace”)
- Asynchronous operations

Issue #1: Race Conditions





Definition

- "A *race condition* is a flaw in a system or process where the output exhibits unexpected critical dependence on the relative timing of events." (wikipedia)

Application to threads

- Execution of threads is controlled by the operating system (OS)
- It is possible for threads to be pre-empted and another thread to run ⇒ can't assume anything about order
- While easy to understand, race conditions can be hard to locate and debug

Example

- Thread 1: compute sqrt of number
- Thread 2: update number on condition

Code:

```
thread1() {
  if (x < 0)
    y = 0;
  else
    y = sqrt(x);
}

thread2() {
  if (event) x = x – 1;
}
```

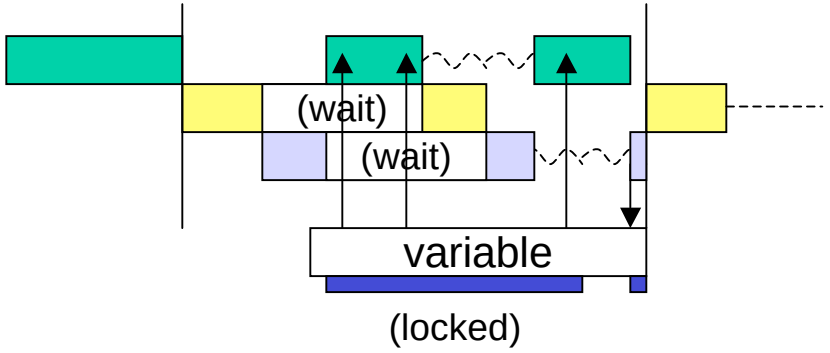
Mutual Exclusion (mutex)

Solution: exclude overlapping access

- Semaphores introduced by Djikstra in 1960s to handle this problem
- Key idea: protect “critical sections” of code by setting a “mutex”
- Mutex_lock: wait for mutex to be unblocked (if it isn’t already), then set
  - While a mutex_lock is being blocked, the OS can execute code
- Mutex_unlock: unset the mutex

Atomicity

- Operating systems need to insure that mutexes are “atomic” operations - no instructions executed while checking and setting the flag
- If this doesn’t happen, you can get a race condition in setting the flag (which is what we are trying to avoid…)



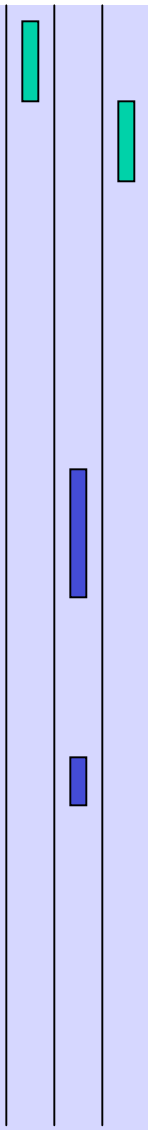

```
thread1() {
  mutex_lock(xmtx);
  if (x < 0)
    y = 0;
  else
    y = sqrt(x);
  mutex_release(xmtx);
}

thread2() {
  mutex_lock(xmtx);
  if (event) x = x – 1;
  mutex_release(xmtx);
}
```

Critical Section

Critical Section

Issue #2: Deadlocks

```
 1 thread1() {
 2   mutex_lock(xmtx);
 3   if (x < 0) x = 0;
 4   mutex_lock(ymtx);
 5   y = sqrt(-x);
 6   mutex_lock(ymtx)
 7   mutex_release(xmtx);
 8 }
 9
10 thread2() {
11   mutex_lock(ymtx);
12   if (y == 0) compute();
13   mutex_unlock(ymtx);
14 }
15
16 compute() {
17   mutex_lock(xmtx);
18   if (event) x = x – 1;
19   mutex_release(xmtx);
20 }
```



Possible execution

- Thread 1 executes up to line 3
  - Locks xmtx mutex
- Switch to thread 2
- Thread 2 executes through line 12
  - Locks ymtx mutex
- Compute() blocks on xmtx mutex
- Switch to thread 1
- Thread 1 blocks on ymtx mutex
- (no further execution)

Remarks

- Easy to fix, but sometimes hard to *spot* (especially when using subroutines)

Solution: lots of debugging

- Formal tools exist, but generally can't operate at programming code level

Thread Usage

When to use threads

- Main usage is when the program has to wait on a process or resource
- Eliminate threads if they aren't needed (eg, tight interlocking with no waits)

Avoiding deadlocks

- Never put a mutex around a call that might itself block (I/O call, mutex, etc)
- If you have to use nested mutex's, make sure they are in the same order whenever they are invoked

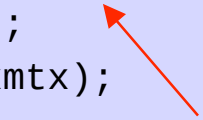
Performance improvements

- Try to keep critical sections as small as possible (avoids excessive waiting)
- Combine accesses to same variables in nearby sections
- Use buffers to minimize lock times

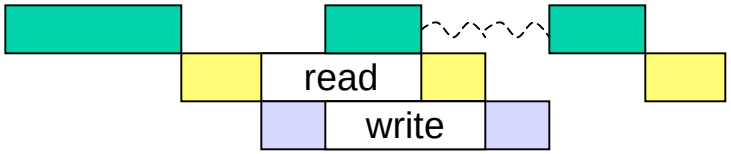
Conditional variables

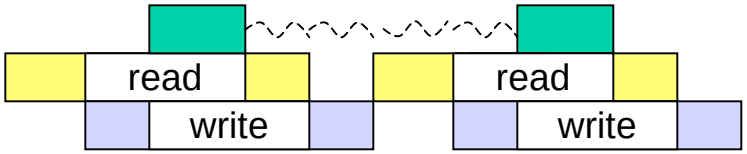
- Allows a thread to sleep until a certain condition is met
- Used in conjuction with a mutex

```
 1 thread1() {
 2   mutex_lock(xmtx);
 3   while (!condition)
 4     cond_wait(&cond, &mutex);
 5   do_something();
 6   mutex_unlock(xmtx);
 7 }
 8
 9 thread2() {
10   mutex_lock(xmtx);
11   // make condition TRUE
12   if (cond)
13     cond_signal(&cond);
14   mutex_unlock(xmtx);
15 }
```



Issue #3: Asynchronous Execution





Executation is non-deterministic

- Operating system determines when to execute individual threads
- Different operating systems will give different sequences of operations
- Avoid tuning scheduling rules to let OS optimize (eg, multi-processor core)

Use mutexes and conditions if needed

- Can insure partial synchronization by using mutexes and conditions, *but*
- Avoid overly constraining threads; can get worse performance than just doing things sequentially

Reasoning about concurrent code

- It is still possible to prove things about multi-threaded execution
- Example: Lyapunov like functions
  - Let V be a positive function whose minimum corresponds to desired state
  - Show that each portion of code does not increase V's value
  - Show that some portions of code decrease value of V
  - Conclude that V will approach minimum value
- Formal methods: temporal logic, unity

POSIX Threads (Pthreads)

Thread creation

- pthread_create — call a function as a new thread of execution
- pthread_exit — terminate the current thread
- pthread_join — wait for a specific thread to exit

Mutexes

- pthread_mutex_init — initialize a mutex
- pthread_mutex_lock — lock a mutex (blocks until mutex is available)
- pthread_mutex_unlock — unlock a mutex (and unblock first blocked threads)
- pthread_mutex_destroy — free up resources associated with a mutex

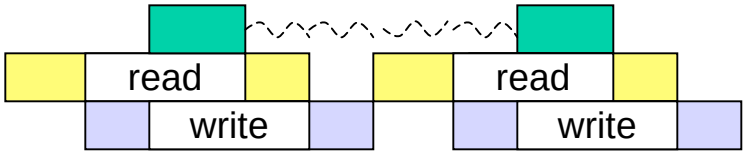
Conditional variables

- pthread_cond_init — initialize a condition
- pthread_cond_wait — wait until condition is satisfied (paired with a mutex)
- pthread_cond_signal — signal that a condition is now satisfied
- pthread_cond_destroy — free up resources associate with a mutex

Read/write locks

- Variation on mutexes that allow multiple unblocking reads

Example: Threaded Control Loop




```
 1 pthread_create(…, sensor, …);
 2 pthread_create(…, actuator, …);
 3 pthread_create(…, control, …);
 4 display();
 5
 6 sensor() {
 7   // initialization
 8   while (1) {
 9     pthread_mutex_lock(smtx);
10     y = read_measurement();
11     r = read_reference();
12     pthread_mutex_unlock(smtx);
13     usleep(S_WAIT_USEC);
14   }
15 }
16
17 actuation() …
```

```
18 control() {
19  // initialization
20   while (1) {
21     pthread_mutex_lock(smtx);
22     err = r - y;
23     pthread_mutex_unlock(smtx);
24
25     xnew = Ac * x + Bc * err;
26
27     pthread_mutex_lock(amtx);
28     u = Cc * x + Dc * err;
29     pthread_mutex_unlock(amtx);
30
31     sleep(C_WAIT_USEC)
32   }
33 }
```

Notes

- Process inputs/outputs asynchronously
- HW: is this OK? Optimal?

Thread Scheduling

Thread scheduling policies

- *FIFO* - threads are called in first in, first out order within each priority level
  - Thread continues to run until a higher priority thread is runnable
  - Threads at same priority must block in order for other threads to run
- *Round-robin* - each thread is called in sequence, within priority level
  - Thread runs for fixed period of time before it is pre-empted
- *Other* - implementation specific
  - Operating system defines how threads are scheduled
  - This is the default (and undefined!)

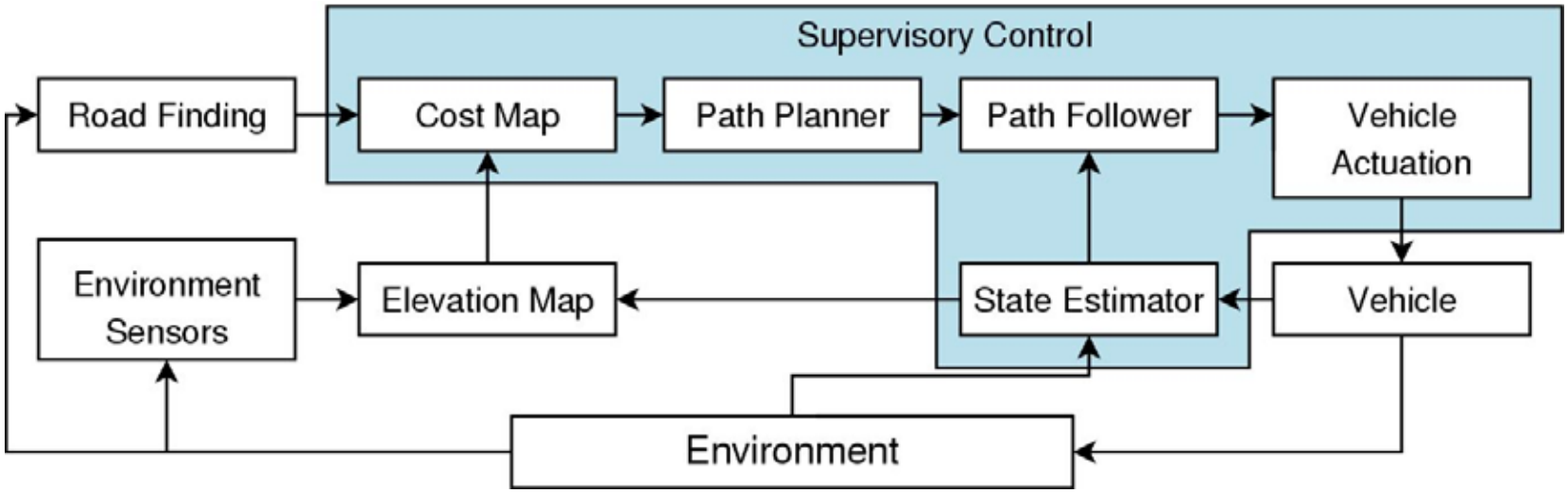
Homework

- Write a simple multi-threaded program using pthreads that reads numbers from an input stream (terminal), averages all numbers that have been read, and prints out the average once a second [use three threads]

Project Ideas

- Expand sparrow to allow multi-threaded servo and channel (I/O) execution
- Analyze how to best use mutex's for minimizing control latency when reading inputs via the network and writing outputs via (slow) serial ports
- Convert a controller from continuous to discrete for a multi-threaded control system using FIFO or round-robin scheduling

Thread Usage in Alice



Module	Threads
adrive (actuation)	19
trajFollower	10
astate (state estimator)	10
plannerModule	4
fusionMapper	16

Module	Threads
ladarFeeder (5)	8
stereoFeeder (2)	7
road (road follower)	5
superCon	3
DBS	3

* doesn't count heartbeat and logging threads

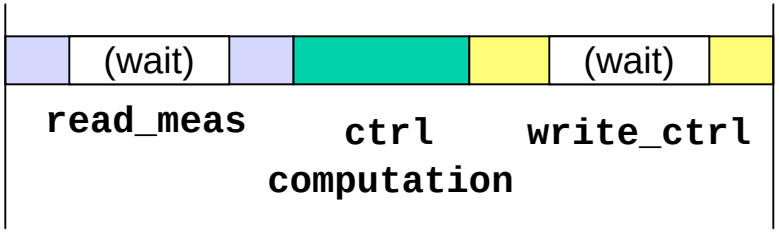
Example: State Client

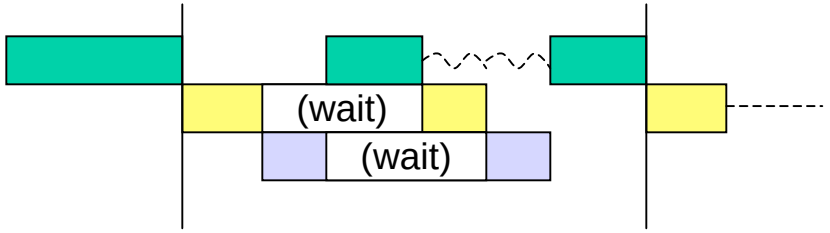
- Asynchronously reads actuator state from adrive via thread
- Passes data back to calling module (eg, trajFollower)

```
void CStateClient::getActuatorStateThread() {
  int actuatorstatesocket =
    m_skynet.listen(SNactuatorstate, ALLMODULES);

  while(m_bRunThreads) {
    if(m_skynet.get_msg(actuatorstatesocket,
      &m_rcvdActuatorstate, sizeof(m_rcvdActuatorstate), 0,
      &pActuatorstateMutex) != sizeof(m_rcvdActuatorstate))
        skynet_error();
    DGCSetConditionTrue(condNewActuatorState);
  }
}

void CStateClient::UpdateActuatorState()
{
  DGClockMutex(&m_actuatorstateMutex);
  memcpy(&m_actuatorState, &m_rcvdActuatorstate, sizeof(…));
  DGCunlockMutex(&m_actuatorstateMutex);
}

void CStateClient::WaitForNewActuatorState() {
  DGCWaitForConditionTrue(condNewActuatorState);
  UpdateActuatorState();
  condNewActuatorState.bCond = false;
}
```

- Thread to read msgs
- Infinite loop
- Read msg (blocks until available)
- Unblock any-one waiting
- Copy state into buffer
- Use mutex to insure completeness
- Block until new state msg arrives

Summary: Multi-Threaded Control Systems





Advantages

- Allows more efficient processor usage when waiting for hardware
- Convenient method for handling independent, parallelizable tasks

Cautions

- Race conditions
- Deadlocking
- Asynchronous execution
- Debugging

Open Issues for Control Theory

- How should we implement feedback controllers in a multi-threaded, asynchronous environment (and does it matter)?
- How do we verify that multi-threaded programs satisfy the control design specification and designer's intent (or is this automatic)?
- How do we implement multi-rate controllers (of the sort that Giotto is designed to handle) in a threaded process?