Control of Time-Varying Behavior

Can often express a “mission” in terms of a sequence of sub-tasks (or a plan)
• But: we also want to handle contingencies when they arrive

Finite state machines are a simple way of expressing such plans and contingencies
Finite State Machines (FSMs)

Pure FSM is composed of:

- A set of states
- A set of possible inputs (or events)
- A set of possible outputs (or actions)
- A transition function:
  - Given the current state and an input: defines the output and the next state
Finite State Machines (FSMs)

States:

- Represent all possible “situations” that must be distinguished
- At any given time, the system is in exactly one of the states
- There is a finite number of these states
Finite State Machines (FSMs)

An example: a 3-bit counter that increments when “count” input is received

- States: ?
Finite State Machines (FSMs)

An example: a counter

- States: the different combinations of the digits: 000, 001, 010, ... 111

- Inputs: ?
Finite State Machines (FSMs)

An example: a counter

• Inputs (events):
  – Only one: “count”
  – We will call this “C”

• Outputs: ?
Finite State Machines (FSMs)

An example: a counter

• Outputs: same as the set of states

• Transition function: ?
Finite State Machines (FSMs)

An example: a counter

• Transition function:
  – On the count event, transition to the next highest value
FSM Example: Synchronous Counter

A Graphical Representation:

A set of states
FSM Example:
Synchronous Counter

A transition

C/001 → 001
FSM Example:
Synchronous Counter

A transition

The event
FSM Example: Synchronous Counter

A transition

The output
FSM Example: Synchronous Counter

A transition

The output: The Zyante book calls these “Mealy Actions”
FSM Example: Synchronous Counter

The next transition

000 -> 001
001 -> 010
C/010
010 -> 011
C/001
011 -> 100
110

111
101

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FSM Example: Synchronous Counter

The next transition
FSM Example: Synchronous Counter

The full transition set

C/000 → 000
C/001 → 001
C/010 → 010
C/011 → 011
C/100 → 100
C/101 → 101
C/110 → 110
C/111 → 111
C/010 → 010
C/011 → 011
C/100 → 100
C/101 → 101
C/110 → 110
C/111 → 111
FSM Example: Synchronous Counter

Initial condition

- **Initial condition**: x/000
- **Transitions**:
  - C/000: 000 → 001
  - C/001: 000 → 001
  - C/001: 001 → 010
  - C/010: 001 → 010
  - C/010: 010 → 011
  - C/011: 010 → 011
  - C/011: 011 → 100
  - C/101: 011 → 101
  - C/110: 101 → 110
  - C/110: 110 → 111
  - C/111: 111 → 000
  - C/111: 110 → 111
  - C/101: 100 → 111
  - C/101: 101 → 111

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Example II: An Up/Down Counter

Suppose we have two events (instead of one): Count up and count down

- How does this change our state transition diagram?
Example II: An Up/Down Counter

From state 000, there are now two possible transitions

U/001
D/111
Example II: An Up/Down Counter

Likewise for state 001…
Example II: An Up/Down Counter

The full transition set
FSMs and Control

How do we relate FSMs to Control?

• States are?
FSMs and Control

How do we relate FSMs to Control?

- States are our memory of recent inputs
- Inputs are?
FSMs and Control

How do we relate FSMs to Control?

• States are our memory of recent inputs

• Inputs are some processed representation of what the sensors are observing

• Outputs are?
FSMs and Control

How do we relate FSMs to Control?

• States are our memory of recent inputs

• Inputs are some processed representation of what the sensors are observing

• Outputs are the control actions
  – These are typically “high level” actions: e.g., set the goal orientation to 125 degrees
FSMs: A Control Example

Suppose we have a vending machine:

- Accepts dimes and nickels
- Will dispense one of two things once $.20 has been entered: Jolt or Buzz Water
  - The “user” requests one of these by pressing a button
- Ignores select if < $.20 has been entered
- Immediately returns any coins above $.20
Vending Machine FSM

What are the states?
Vending Machine FSM

What are the states?

- $0
- $.05
- $.10
- $.15
- $.20
Vending Machine FSM

What are the inputs/events?
Vending Machine FSM

What are the inputs/events?

- Input nickel (N)
- Input dime (D)
- Select Jolt (J)
- Select Buzz Water (BW)
Vending Machine FSM

What are the outputs?
What are the outputs?

• Return nickel (RN)
• Return dime (RD)
• Dispense Jolt (DJ)
• Dispense Buzz Water (DBW)
• Nothing (Z)
Vending Machine Design

What is the initial state?
Vending Machine Design

What is the initial state?

• \( S = $0 \)
Vending Machine Design

What can happen from $S = \$0$?

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Vending Machine Design

What can happen from $S = $0?  

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<tr>
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</thead>
<tbody>
<tr>
<td>N</td>
<td>$.05</td>
<td>Z</td>
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<tr>
<td>D</td>
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<td>Z</td>
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<tr>
<td>J</td>
<td>$0</td>
<td>Z</td>
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<tr>
<td>BW</td>
<td>$0</td>
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</table>

What does this part of the diagram look like?
Vending Machine Design

A piece of the state diagram:

![State diagram for vending machine](image)
Vending Machine Design

What can happen from $S = \$0.05$?

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</table>
Vending Machine Design

What can happen from \( S = \$0.05 \)?

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<tr>
<td>BW</td>
<td>$.05</td>
<td>Z</td>
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</table>

What does the modified diagram look like?
Vending Machine Design

A piece of the state diagram:
Vending Machine Design

What can happen from $S = $0.10?  

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</table>
Vending Machine Design

What can happen from S = $0.10?

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<tr>
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<tbody>
<tr>
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Vending Machine Design

A piece of the state diagram:
Vending Machine Design

What can happen from $S = $0.15?

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</table>
**Vending Machine Design**

What can happen from $S = $0.15?

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Vending Machine Design

A piece of the state diagram:
Vending Machine Design

Finally: what can happen from $S = 0.20$?

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Finally, what can happen from $S = \$0.20$?

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<tr>
<td>BW</td>
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<td>DBW</td>
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</table>
Vending Machine Design

The complete state diagram:
• End for day…
Finite State Machines

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FSMs III
Control of Time-Varying Behavior

Can often express a “mission” in terms of a sequence of sub-tasks (it is a plan!)

• But: we also want to handle contingencies when they arrive

Finite state machines are a simple way of expressing such plans and contingencies
Vending Machine FSM

- **$0**: J/Z BW/Z, x/Z
- **$.05**: N/Z D/Z
- **$.10**: J/Z BW/Z, D/Z, J/Z BW/Z, N/Z
- **$.15**: J/Z BW/Z, N/Z D/RN
- **$.20**: J/Z BW/Z, D/Z, J / DJ BW / DBW
Finite State Machines (FSMs)

Pure FSM form is composed of:

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• A set of possible inputs (or events)
• A set of possible outputs (or actions)
• A transition function:
  – Given the current state and an input: defines the output and the next state
FSMs and Control

How do we relate FSMs to Control?

• States are ?
FSMs and Control

How do we relate FSMs to Control?
• States are our memory of recent inputs
• Inputs/events are ?
FSMs and Control

How do we relate FSMs to Control?

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  – These are typically “high level” actions: e.g., set the goal orientation to 125 degrees
A Robot Control Example

Consider the following task:
• The robot is to move toward the first beacon that it “sees”
• The robot searches for a beacon in the following order: right, left, front
• Once beacon is found, move toward it and stop once the beacon is reached

What is the FSM representation?
Robot Description

Mobile robot with sensor turret on top

- Mobile robot turns take time
- Turret turns are relative to the mobile base and do not take time
Events

- Robot Turn Complete (TC)
- Beacon (B)
- No Beacon (NB)
Actions

- Look left (LL): turn turret to be facing left (relative to the mobile base)
- Look right (LR)
- Look forward (LF)
- Turn left (TL): initiate a turn of the robot base by 90 degrees to the left
- Turn right (TR): initiate right turn
- Move forward (F): initiate forward movement
- Stop (S)
Robot Control Example II

Consider the following task:
• The robot must lift off to some altitude
• Translate to some location
• Take pictures
• Return to base
• Land
• At any time: a detected failure should cause the craft to land

What is the FSM representation?
Vending Machine FSM

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FSMs and Control

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FSMs in C


define FSM step:
  static State state = STATE_0;  // Initial state

  <do some processing of the sensory inputs>
  switch(state) {
    case STATE_0:
      <handle state 0>
      break;
    case STATE_1:
      <handle state 1>
      break;
    case STATE_2: ...  
  }

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FSMs in C (some other possibilities)

fsm_step() {
    static State state = STATE_0; // Initial state

    <do some processing of the sensory inputs>
    switch(state) {
        case STATE_0:
            <handle state 0>
            break;
        case STATE_1:
            <handle state 1>
            break;
        case STATE_2: ...
    }
    <do some low-level control>
}
Handling Each State

- You will need to provide code that handles the event processing for each state

- Specifically:
  - You need to handle each event that can occur
  - For each event, you must specify:
    - What action is to be taken
    - What the next state is
Handling Each State

In our vending machine example:

• Events are easy to describe (only a few things can happen)

• It is convenient in this case to also “switch” on the event
case STATE_10cents:
    // $.10 has already been deposited
switch(event) {
    case EVENT_NICKEL:  // Nickel
        state = STATE_15cents;  // Transition to $.15
        break;
    case EVENT_DIME:    // Dime
        state = STATE_20cents;  // Transition to $.2
        break;
    case EVENT_JOLT:    // Select Jolt
    case EVENT_BUZZ:    // Select Buzzwater
        display_NOT_ENOUGH();
        break;
    case EVENT_NONE:    // No event
        break;               // Do nothing
};
break;
Handling Each State

Some events do not fall neatly into one of several categories

• This precludes the use of the “switch” construct for events

• For example: an event that occurs when our hovercraft reaches a goal orientation

• For these continuous situations, we typically use an “if” construct …
FSMs in C: Processing for Individual States

```c

\begin{verbatim}
case STATE_MISSION_PHASE_3:
    if(heading_error < 10.0 &&
        heading_error > -10.0)
    {
        // Accelerate forward!
        desired_velocity = {.2, 0};
        state = STATE_MISSION_PHASE_4;
    }
    break;
\end{verbatim}
```
FSMs in C: Processing for Individual States

```c
case STATE_MISSION_PHASE_4:
  if(distance_left < 20.0 ||
     distance_right < 20.0)
  {
    // Brake!
    desired_velocity = {0, 0};
    counter = 0;    // Reset the clock
    state = STATE_MISSION_PHASE_5;
  }
  break;
```

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FSMs in C: Processing for Individual States

case STATE_MISSION_PHASE_5:
    if(counter > 20)
    {
        // Assuming dt=50ms, one second has
        // gone by since we
        // started the brake
        heading_goal = heading_goal - 90.0;
        if(heading_goal <= -180.0) heading_goal += 360;
        state = STATE_MISSION_PHASE_6;
    }
    break;

REMEMBER: counter is being incremented once per control cycle (outside of the FSM code)
FSM Implementation Notes

• FSM code should not contain delays or waits
  – No delay_ms() or while(…){}
  – Remember that your FSM code will be called once per control cycle: use “if” to check for an event during that control cycle

• Use LEDs and/or fprintf() to indicate current state

• Implement and test incrementally
FSM Implementation Notes

For your project: you will use an enumerated data type to represent your set of states.

• Allows us to be very clear what the possible values are

• Affords type checking by the compiler
Mission-Level Control

• In this example (and in your project), the job of the FSM is to worry about sequencing the high-level steps in a task

• We leave the details of sensing and action to other tasks

• Communication between the tasks is through variables declared in global memory