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 form 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

000 → 001

010 → 011

100

101

110

111
FSM Example: Synchronous Counter

A transition

The event
FSM Example: Synchronous Counter

A transition

The output
FSM Example:
Synchronous Counter

The next transition
FSM Example: Synchronous Counter

The next transition
FSM Example: Synchronous Counter

The full transition set

```
000  001  010  011  100  101  110  111
```

Graph:

- 000 -> 001
- 001 -> 010
- 010 -> 011
- 011 -> 100
- 100 -> 101
- 101 -> 110
- 110 -> 111
- 111 -> 000
FSM Example: Synchronous Counter

Initial condition

```
x/000
  c/000
  c/001
  000
  001
  010
  011
  100
  101
  110
  111
  c/010
  c/011
```
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:

- From state 000, an up transition (U/001) leads to state 001.
- From state 000, a down transition (D/111) leads to state 111.

Possible next states:
- From state 001, there is a transition to state 010.
- From state 001, there is a transition to state 011.
- From state 100, there is a transition to state 101.
- From state 100, there is a transition to state 110.
- From state 100, there is a transition to state 111.
- From state 101, there is a transition to state 110.
- From state 101, there is a transition to state 111.
- From state 110, there is a transition to state 111.
Example II: An Up/Down Counter

Likewise for state 001…

- 000
  - U/001
  - D/000
- 001
  - U/010
- 010
  - D/111
- 111

- 110
- 100
- 101
- 011
- 010
Example II: An Up/Down Counter

The full transition set

```
000 → 001: U/000, D/000
001 → 010: U/010, D/001
010 → 011: U/011
011 → 100: U/100
100 → 101: U/101
101 → 110: U/110
110 → 111: U/111
111 → 000: U/001, D/111
```

Andrew H. Fagg: Embedded Real-Time Systems: FSMs
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
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?
Vending Machine FSM

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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<tr>
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**Vending Machine Design**

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

What does this part of the diagram look like?

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

A piece of the state diagram:

![State Diagram](image-url)
Vending Machine Design

What can happen from $S = 0.05$?

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Vending Machine Design

What can happen from S = $0.05?

What does the modified diagram look like?

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Vending Machine Design

A piece of the state diagram:
### Vending Machine Design

What can happen from S = $0.10? 

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### Vending Machine Design

What can happen from $S = $0.10?

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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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Vending Machine Design

What can happen from S = $0.15?

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Vending Machine Design

A piece of the state diagram:
Finally: what can happen from $S = 0.20$?

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</table>
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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</tbody>
</table>
Vending Machine Design

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

[Diagram of a finite state machine with states and transitions labeled with values and symbols such as J/Z, BW/Z, x/Z, N/Z, D/Z, and J / DJ, BW / DBW.]

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  • Outputs are the control actions
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

- 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): turn robot base by 90 degrees to the left
- Turn right (TR)
- Move forward (F)
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?
FSMs As Controllers

Must bridge the gap between the FSM and the low- and mid-level controllers

• Events:
  – Abstraction of sensor or internal state

• Actions:
  – Modify mid- or low-level control behavior
Next Time

• Project 8
FSMs in C

State state = STATE_0;  // Initial state
while(1) {
    //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: ...
FSMs in C (some other possibilities)

State state = STATE_0;  // Initial state
while(1) {
    <do some processing of the sensory inputs>
    switch(state) {
        case STATE_0:
            <handle state 0>
            break;
        :
        default:
            <handle default case>
            break;
    }
    <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
FSMs in C: Processing for Individual States

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
case STATE_MISSION_PHASE_3:
    if(heading_error < 100 &&
       heading_error > -100)
    {
        // Accelerate forward!
        forward_thrust = 126;
        state = STATE_MISSION_PHASE_4;
    }
    break;
```
FSMs in C: Processing for Individual States

```c
: case STATE_MISSION_PHASE_4:
    if(distance_left < 200 ||
        distance_right < 200)
    {
        // Brake!
        forward_thrust = 0;
        middle_thrust_magnitude(300);
        middle_thrust_dir(BRAKE);
        state = STATE_MISSION_PHASE_5;
        counter = 0;    // Reset the clock
    }
break:
```
FSMs in C: Processing for Individual States

case STATE_MISSION_PHASE_5:
    if(counter > 20)
    {
        // One second has gone by since we
        // started the brake: Stop the brake

        middle_thrust_magnitude(100);
        middle_thrust_dir(HOVER);
        forward_thrust = 100;
        heading_goal = -900;
        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: use an enumerated data type to represent your set of states.