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

001

010

011

100

101

110

111
FSM Example: Synchronous Counter

A transition

The event

C/001

001

000

010

011

100

101

110

111
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 (C/001)
001 > 010 (C/010)
010 > 011
011
100
101
110
111
FSM Example: Synchronous Counter

The next transition
FSM Example: Synchronous Counter

The full transition set

000 001 010 011 100 101 110 111

C/000 C/001 C/010 C/011 C/100 C/101 C/110 C/111

Andrew H. Fagg: Embedded Real-Time Systems: FSMs
FSM Example:
Synchronous Counter

Initial condition

000 001 010 011 100 101 110 111

C/000 C/001 C/010 C/011 C/100 C/101 C/110 C/111

x/000
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

000 \rightarrow 001 \quad U/001

000 \rightarrow 111 \quad D/111

001

010

011

100

101

110

111
Example II: An Up/Down Counter

Likewise for state 001…

[Diagram of state transitions]
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
• Questions?
• Quiz…
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?
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
What can happen from $S = \$0$?

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

A piece of the state diagram:

$0 \rightarrow \$.05 \rightarrow $.10 \rightarrow x/Z \rightarrow N/Z \rightarrow D/Z \rightarrow J/Z \rightarrow BW/Z \rightarrow $0
Vending Machine Design

What can happen from $S = $0.05?

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</table>
Vending Machine Design

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

What does the modified diagram look like?

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<tr>
<td>J</td>
<td>$.05</td>
<td>Z</td>
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<tr>
<td>BW</td>
<td>$.05</td>
<td>Z</td>
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</table>
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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<td>BW</td>
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<td>Z</td>
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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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<tr>
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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>
<tr>
<td>BW</td>
<td>$0</td>
<td>DBW</td>
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Vending Machine Design

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

$0

$.05

$.10

$.15

$.20

D/Z

J/Z

BW/Z

N/Z

D/Z

N/Z

BW/Z

D/RN

J/Z

N/RN

D/RD

J / DJ

BW / DBW

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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

$0$

$.05$

$.10$

$.15$

$.20$

x/Z

J/Z

BW/Z

N/Z

D/Z

N/Z

J/Z

BW/Z

N/Z

D/RN

N/RN

D/RD

J / DJ

BW / DBW

Andrew H. Fagg: Embedded Real-Time Systems: FSMs
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Pure FSM form is composed of:

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FSMs and Control

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FSMs and Control

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• Outputs are the control actions
  – 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): 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 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 …
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: 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
FSMs in C: Mixing High and Low-Level Control

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>
}
FSMs in C:
Mixing High and Low-Level Control

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;
    }
    // We need to call this every time through the loop
    position_derivative_control();
}
Next Time

• Project 9