Module 7

Lecture: Finite State Machines - Theory
Finite State Machines - Theory

You will learn in this module

- C programming fundamentals
  - Arrays
  - Pointers
  - Structures
  - Time delays

- Develop debugging techniques such as
  - Watch windows
  - Breakpoints
  - Heart beats

- Solve problems with finite state machines
  - States, tables, graphs, input, outputs
  - Mealy versus Moore

- Design controller for a line tracking robot
  - Traffic light controller
  - Line-following robot
Abstraction

Software abstraction:

- Define a problem
  - Minimal set of basic concepts
  - Abstract principles / processes
- Separation of policy and mechanisms
  - Interfaces define what it does (policy)
  - Implementations define how it works (mechanisms)
- Straightforward, mechanical path to implementation

Three advantages of abstraction are:

- Faster to develop
- Easier to debug (prove correct) and
- Easier to change

Finite State Machine Rules

1. Simple structure: Input->Process->Output
2. Information is encoded by being in a state.
3. FSM controllers are very simple:
   e.g., output, wait, input, go to next state.
4. Complexity is captured in the state graph
5. There is a 1-1 mapping between state graph and
   the software implementation
Finite State Machine (FSM)

What is a Finite State Machine?
- Set of inputs, outputs, states and transitions
- State graph defines input/output relationship

What is a state?
- Description of current conditions
- What you believe to be true

What is a state transition graph (or table)?
- Graphical interconnection between states

What is a controller?
- Software that inputs, outputs, changes state
- Accesses the state graph
Finite State Machine (FSM)

What is a Finite State Machine (FSM)?

- Inputs (sensors)
- Outputs (actuators)
- Controller
- State transition graph
Traffic Light Controller

State Transition Graph (STG)

State Transition Table (STT)

<table>
<thead>
<tr>
<th>State   \ Input</th>
<th>00</th>
<th>01</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>goN (100001,30)</td>
<td>goN</td>
<td>waitN</td>
<td>goN</td>
<td>waitN</td>
</tr>
<tr>
<td>waitN (100010,5)</td>
<td>goE</td>
<td>goE</td>
<td>goE</td>
<td>goE</td>
</tr>
<tr>
<td>goE (001100,30)</td>
<td>goE</td>
<td>goE</td>
<td>waitE</td>
<td>waitE</td>
</tr>
<tr>
<td>waitE (010100,5)</td>
<td>goN</td>
<td>goN</td>
<td>goN</td>
<td>goN</td>
</tr>
</tbody>
</table>
const struct State {
    uint32_t Out;     // 6-bit output
    uint32_t Time;    // 1 ms units
    uint32_t Next[4]; // list of next states
};
typedef const struct State State_t;

#define goN 0
#define waitN 1
#define goE 2
#define waitE 3
State_t FSM[4] = {
    {0x21, 30000, {goN,waitN,goN,waitN}},
    {0x22, 5000, {goE,goE,goE,goE}},
    {0x0C, 30000, {goE,goE,waitE,waitE}},
    {0x14, 5000, {goN,goN,goN,goN}}
};
void main(void) {
    uint32_t cs;    // index of current state
    uint32_t input; // car sensor input
    Traffic_Init(); // initialize ports and timer
    cs = goN;       // initial state
    while(1){
        // 1) set lights to current state's Out
        P4->OUT = (P4->OUT&~0x3F)|(FSM[cs].Out);
        // 2) specified wait for this state
        Clock_Delay1ms(FSM[cs].Time);
        // 3) input from car detectors
        input = (P5->IN&0x03);
        // 4) next depends on state and input
        cs = FSM[cs].Next[input];
    }
}
const struct State {
    uint32_t Out;     // 6-bit output
    uint32_t Time;    // 1 ms units
    const struct State *Next[4]; // next states
};

typedef const struct State State_t;

#define goN    &FSM[0]
#define waitN  &FSM[1]
#define goE    &FSM[2]
#define waitE  &FSM[3]

State_t FSM[4] = {
    {0x21, 30000, {goN, waitN, goN, waitN}},
    {0x22, 5000, {goE, goE, goE, goE}},
    {0x0C, 30000, {goE, goE, waitE, waitE}},
    {0x14, 5000, {goN, goN, goN, goN}}
};

00,10 01,11 00,01,10,11 00,01,10

00,11 00,01 10,11 10,11

00,01 00,01 00,01 00,01
void main(void) {
    State_t *pt;    // pointer to current state
    uint32_t input; // car sensor input
    Traffic_Init(); // initialize ports and timer
    pt = goN;       // initial state
    while(1){
        // 1) set lights to current state's Out
        P4->OUT = (P4->OUT&~0x3F)|(pt->Out);
        // 2) specified wait for this state
        Clock_Delay1ms(pt->Time);
        // 3) input from car detectors
        input = (P5->IN&0x03);
        // 4) next depends on state and input
        pt = pt->Next[input];
    }
}
Mealy versus Moore

- **Moore FSM**
  - Output value depends on current state
  - Significance is the state
  - Input: when to change state
  - Output: how to be or what to do while in that state

- **Mealy FSM**
  - Output value depends on input and current state
  - Significance is the state transition
  - Input: when to change state
  - Output: how to change state
Summary

- **Abstraction**
  - Define a problem
    - Concepts / principles / processes
  - Separation of policy and mechanisms
    - Interfaces define what it does (policy)
    - Implementations define how it works (mechanisms)

- **Finite State Machines**
  - Inputs (sensors)
  - Outputs (actuators)
  - Controller
  - State graph
    - States
    - Implementations define how it works (mechanisms)
Module 7
Lecture: Finite State Machines – Line Follower
Finite State Machine Example

You will learn in this lecture
- Design controller for a line tracking robot
  - Two sensor inputs
  - Two motor outputs
Simple Line Tracker

Two Sensors
- 1,1  on line
- 1,0  off to the right
- 0,1  off to the left
- 0,0  lost

Two Motors
- 1,1  go straight
- 1,0  turn right
- 0,1  turn left

Left, Right

Left, Right
Strategy
Strategy
Strategy
Strategy
Strategy
Strategy
Strategy
Strategy
Strategy
Strategy
Strategy
Strategy
Strategy
Strategy

Left sensor = 0
Strategy

Left sensor = 0

Slow down right wheel

100%

50%
Strategy

Left sensor = 0

Slow down right wheel

100%

50%
Strategy

Go straight

100%

100%
Strategy
Strategy
Strategy

Right sensor = 0
Strategy

Right sensor = 0

50%

100%

Slow down left wheel
Strategy

Right sensor = 0

- 50%: Slow down left wheel
- 100%
Strategy

Slow down left wheel

Right sensor = 0
Strategy

Right sensor = 0

50%

100%

Slow down left wheel
Strategy
### States

<table>
<thead>
<tr>
<th>State</th>
<th>Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1,1</td>
</tr>
<tr>
<td>Left</td>
<td>0,1</td>
</tr>
<tr>
<td>Right</td>
<td>1,0</td>
</tr>
</tbody>
</table>

Motors respond in 100ms, so run FSM every 50ms
Simple Line Tracker

Two Sensors
1,1 on line
0,1 off to the left
1,0 off to the right
0,0 lost

Left, Right
### State Transition Table

<table>
<thead>
<tr>
<th>State</th>
<th>Motor</th>
<th>In=0,0</th>
<th>In=0,1</th>
<th>In=1,0</th>
<th>In=1,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1,1</td>
<td></td>
<td></td>
<td></td>
<td>Center</td>
</tr>
<tr>
<td>Left</td>
<td>1,0</td>
<td></td>
<td></td>
<td></td>
<td>Center</td>
</tr>
<tr>
<td>Right</td>
<td>0,1</td>
<td></td>
<td></td>
<td></td>
<td>Center</td>
</tr>
</tbody>
</table>

```c
State_t fsm[3]={
    {0x03, 1, {}},
    {0x02, 1, {}},
    {0x01, 1, {Center}}
};
```

*On the line, so go straight*
State Transition Table

<table>
<thead>
<tr>
<th>State</th>
<th>Motor</th>
<th>In=0,0</th>
<th>In=0,1</th>
<th>In=1,0</th>
<th>In=1,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1,1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>1,0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>0,1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Off to left, so toggle right motor, turn right

State_t fsm[3]=
{0x03, 1, {Left, 0x03, 1, {Center, 0x02, 1, {}}, 0x01, 1, {}}};
### State Transition Table

<table>
<thead>
<tr>
<th>State</th>
<th>Motor</th>
<th>In=0,0</th>
<th>In=0,1</th>
<th>In=1,0</th>
<th>In=1,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1,1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>1,0</td>
<td></td>
<td></td>
<td></td>
<td>Left</td>
</tr>
<tr>
<td>Right</td>
<td>0,1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Way off to left, so stop right motor, turn right

**State_t fsm[3]=**

```c
{0x03, 1, {  
{0x02, 1, { Left,  
{0x01, 1, {  

Center }},  
Center }},  
Center }  
```

- **Left**: 1,0
- **Center**: 1,1
- **Right**: 0,1
State Transition Table

<table>
<thead>
<tr>
<th>State</th>
<th>Motor</th>
<th>In=0,0</th>
<th>In=0,1</th>
<th>In=1,0</th>
<th>In=1,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1,1</td>
<td></td>
<td></td>
<td></td>
<td>Right</td>
</tr>
<tr>
<td>Left</td>
<td>1,0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>0,1</td>
<td></td>
<td></td>
<td></td>
<td>Center</td>
</tr>
</tbody>
</table>

Off to right, so toggle left motor, turn left

State_t fsm[3]=
{0x03, 1, {{Right} }},
{0x02, 1, {{Center} }},
{0x01, 1, { }};
**State Transition Table**

<table>
<thead>
<tr>
<th>State</th>
<th>Motor</th>
<th>ln=0,0</th>
<th>ln=0,1</th>
<th>ln=1,0</th>
<th>ln=1,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1,1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>1,0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>0,1</td>
<td></td>
<td></td>
<td></td>
<td><strong>Right</strong></td>
</tr>
</tbody>
</table>

```c
State_t fsm[3]=
{0x03, 1, { },
{0x02, 1, { },
{0x01, 1, { **Right**, },
};
```

*Way off to right, so stop left motor, turn left*
State Transition Table

<table>
<thead>
<tr>
<th>State</th>
<th>Motor</th>
<th>In=0,0</th>
<th>In=0,1</th>
<th>In=1,0</th>
<th>In=1,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1,1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>1,0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>0,1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Weird things that shouldn't happen

State_t fsm[3]=
{
{0x03, 1, { Right, }
{0x02, 1, { Right }
{0x01, 1, { Left, }
}
};
**State Transition Table**

<table>
<thead>
<tr>
<th>State</th>
<th>Motor</th>
<th>In=0,0</th>
<th>In=0,1</th>
<th>In=1,0</th>
<th>In=1,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1,1</td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Center</td>
</tr>
<tr>
<td>Left</td>
<td>1,0</td>
<td>Left</td>
<td>Center</td>
<td>Right</td>
<td>Center</td>
</tr>
<tr>
<td>Right</td>
<td>0,1</td>
<td>Right</td>
<td>Left</td>
<td>Center</td>
<td>Center</td>
</tr>
</tbody>
</table>

Motors respond in 100ms, so run FSM every 10ms

State_t fsm[3]=
{0x03, 1, {Right, Left, Right, Center }},
{0x02, 1, {Left, Center, Right, Center }},
{0x01, 1, {Right, Left, Center, Center }}
struct State {
    uint32_t out;                // 2-bit output
    uint32_t delay;              // time to delay in 1ms
    const struct State *next[4]; // Next if 2-bit input is 0-3
};
typedef const struct State State_t;

#define Center  &fsm[0]
#define Left    &fsm[1]
#define Right   &fsm[2]
State_t fsm[3]= {
    {0x03, 50, { Right, Left, Right, Center }}, // Center
    {0x02, 50, { Left, Center, Right, Center }}, // Left
    {0x01, 50, { Right, Left, Center, Center }}  // Right
};
State_t *Spt;     // pointer to the current state
uint32_t Input;   // 00=off, 01=right, 10=left, 11=on
uint32_t Output;  // 3=straight, 2=turn right, 1=turn left
int main(void){
    Clock_Init48MHz();
    Motor_Stop(); // initialize DC motors
    Spt = Center;
    while(1){
        Output = Spt->out;                // set output from FSM
        Motor_Output(Output);             // do output to two motors
        Clock_Delay1ms(Spt->delay);       // wait
        Input = Reflectance_Center(1000); // read sensors
        Spt = Spt->next[Input];           // next depends on input and state
    }
}
Summary

- Abstraction
  - Define a problem
    - Concepts / principles / processes
  - Separation of policy and mechanisms
    - Interfaces define what it does (policy)
    - Implementations define how it works (mechanisms)

- Finite State Machines
  - Inputs (sensors)
  - Outputs (actuators)
  - Controller
  - State graph
    - States
    - Implementations define how it works (mechanisms)
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