國立交通大學

資訊科學與工程研究所

碩 士 論 文

以 AFSM 為基礎的感測/驅動控制混合程式驗證

Hybrid Program Verification for AFSM-based Sensory-Motor Control

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中 華 民 國 九 十 五 年 七 月

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ABSTRACT

In this thesis, we develop a method to apply formal verification of Temporal Logic onto an autonomous robot system controlled by Rodney Brooks' Augmented Finite State Machine model.

This method uses some approaches to reduce the complexity of an AFSM-based reactive robot control system (RRCS), so that verification of AFSM-based RRCS can become applicable. These approaches applied onto verification include：(1) State Space Discretization——It is not feasible to verify a system on continuous space-time domain. Therefore, before constructing an AFSM-based RRCS we must transform the system and environment from continuous space domain to discrete space domain. (2) External function——By exporting internal states and kinematic computation of the robot from the model checker using the external function provided by OMocha temporal logic model checker. (3) Elimination of some checking cases——Based on the properties we want to check, we can eliminate some unnecessary checking cases which will never violate the properties.

After using above-mentioned approaches, the results show that the number of all reachable states checked by OMocha and checking time improve greatly.

In this thesis, we reach some accomplishments listed below：

(1) Check the Behaviors of the AFSM-based RRCS by Model Checker——After constructing the AFSM-based RRCS, we describe the "No Collision" property by Temporal Logic, and prove that the robot controlled by the RRCS will never collide with obstacles in

two-dimensional environment.

(2) Improve the Performance of Checking Procedure——After reducing the checking time by the three approaches, the best results show that the checking procedure can be completed in reasonable time.

According to the accomplishments, we can prove that it’s applicable to apply verification onto an AFSM-based RRCS.

以 AFSM 為基礎的感測/驅動控制混合程式驗証

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摘　要

在這篇論文中，我們發展一個方式將時序邏輯正規驗證法，應用在由 Rodney Brooks 所提出的增強化有限態機器(AFSM)所控制的自主性機器人上。

在這個方式中，我們使用了一些方法去簡化以 AFSM 為基礎的感應式機器控制系統(RRCS)的複雜度，讓以 AFSM 為基礎的 RRCS 之驗證能夠有可行性。這些被應用在驗證上的方法包括有：(1)狀態空間離散化——驗證一個在連續定義域上的系統是不可行的。因此，在建構一個以 AFSM 為基礎的 RRCS 之前，我們必須將系統及環境從連續定義域轉換到分散定義域。(2)外部函數——藉由 OMocha 所提供的外部函數，將系統中的內部狀態及運動學上的計算從驗證器中輸出至外部函數。(3) 去除掉不必要的檢驗部分——根據我們所要檢驗的行為特性，我們能夠將必定不會違背此特性的一些檢驗部分去除掉。

在運用了上述的這些方法後，結果中顯示，被 OMocha 檢驗的全部可到達狀態數目及檢驗時間都改善了很多。

在這篇論文中，我們將達成的一些成果列在下面：

(1)用檢驗器檢驗以 AFSM 為基礎的 RRCS 之行為特性——在建構起以 AFSM 為基礎的 RRCS 後，我們用時序邏輯來描述”No_Collision”這個特性，並且證明了被此 RRCS 控制的機器人在二維空間中將永遠不會碰到障礙物。

(2)改善檢驗程序的效率——在藉由三個方法來縮短檢驗時間後，最佳的結果中顯示檢驗程序能夠在合理的時間內被完成。

根據這些成果，我們能夠證明將正規驗證應用在以 AFSM 為基礎的 RRCS 是可行的。

致謝

論文定稿後，我自己重新將論文看了一遍，其中有很多不夠完美的地方，但相信我有盡我所能去做到最好，希望所有在過程中給予我幫助的大家能夠滿意這篇論文所呈現出來的樣貌，這是我唯一能夠回報的。

首先，要感謝邵家健教授不斷耐心地給予我指導，雖然老師講的有些東西我好像永遠沒有弄懂，但我已經從我弄懂的事情中獲得了很多，那已經很足夠了，對於研究、對於人生，您都是我的良師益友。另外，很感激王柏堯老師及黃耿典學長的協助，希望這次的合作成果能夠讓你們滿意，也期望將來能繼續合作將這個題目延伸發展下去。再來，要謝謝實驗室所有的同伴們，過程中互相打氣激勵是一個很重要的動力，在好的研究環境中才會有好的研究成果，很慶幸能夠和大家一起努力，一同營造出這樣一個令人感到舒服有鬥志的氛圍。

最後，要感謝我的父母，謝謝你們的栽培，相信你們看不懂這篇論文，不過其中的每一字一句都是因為你們才存在的。

謝謝大家，也謝謝我自己，辛苦了…

2006/07/26 寫於 620 實驗室

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Chapter 1
Introduction

1.1 Project Objective

How to write modular reusable programs has always been a major challenge to the developers of autonomous robots. Rodney Brooks of MIT proposed a new approach, called *Augmented Finite State Machines (AFSM) [1]*, to program *reactive robot control systems (RRCS)*. The AFSM approach allowed robot programmers to create program modules that control robot behaviors and develop complex robot behaviors by the composition of these AFSM modules.

The purpose of this work is to explore the possibility of using *formal verification* technique to verify certain properties of the behaviors of AFSM controlled robots. Such a verification technique will enable robot programmers to test or "debug" their programs before using them to actually control the robots. The difficulty of this attempt of formal verification lies with the fact that robot motions are carried out continuously on space and time whereas formal verification can only be applied onto systems with limited number of discrete states. Therefore, the challenge is to properly discretize and reduce the number of states of a robot system so that formal verification can become applicable.

1.2 Project Approach

We explore ways to apply formal verification onto AFSM programs by experimenting with following approaches/methods.

(A) State Space Discretization

To verify a system on continuous domain is not applicable. Therefore, before constructing an AFSM-based RRCS we must transform the system and environment from continuous domain to discrete domain. In discretization procedure, there are two parts. (1) Time

Discretization, and (2) Space Discretization. After discretization, the number of states of the system will reduce from infinite to finite so that formal verification can become more applicable.

(B) Using external function to reduce number of states checked by model checker

External functions are written by high-level language(e.g. C language). For following reasons, we can use external function to reduce number of states checked by model checker. (1) During verification procedure, there are some system variables which are irrelevant to behavior verification. Therefore, we can export these variables through external function in order to reduce the number of states checked by model checker, so that the unnecessary loading for model checker will reduce. (2) In a system, some complex computation can't be handled by model checker, because the purpose of model checker is for verification but not suitable for handling complex computation. Therefore, we must export these complex computations through external function.

(C) Eliminate unnecessary checking cases

Based on the properties we want to check, we can eliminate some unnecessary checking cases, because this part of verification procedure will never violate the properties. The overhead of this approach is that we must analyze the behaviors of the system in advance, otherwise, we can't decide which part of verification procedure can be eliminated.

After applying above-mentioned approaches, we hope that formal verification will become applicable for a system on continuous domain originally.

1.3 Outline of Thesis

The rest of this thesis is organized as follows. In Chapter 2, we explain the AFSM-based RRCS and Roving Robot Collision Avoidance Experiment. In Chapter 3, we introduce the concepts of model checking for AFSM-based RRCS. In Chapter 4, we propose the approaches of model checking for AFSM-based RRCS. In Chapter 5, the implementation of roving robot collision avoidance experiment is described in detail. In Chapter 6, we show the results of properties checking of the experiment, and analysis the results. The conclusion and future work are in Chapter 7.

Chapter 2
AFSM-based RRCS and Roving Robot Collision Avoidance Experiment

2.1 Augmented Finite State Machine (AFSM)

The chart of a modularized AFSM module is shown as Fig. 2-1. There are some *states* and *variables* in a module. State transitions are determined according to transition functions between states. These transition functions don't only take *current state* and *inputs* as parameters, but *internal variables*. The inputs come from other modularized AFSM modules; The *outputs* of state transition are sent to other modularized AFSM modules. Transition function of AFSM module is illustrated with Fig. 2-2.

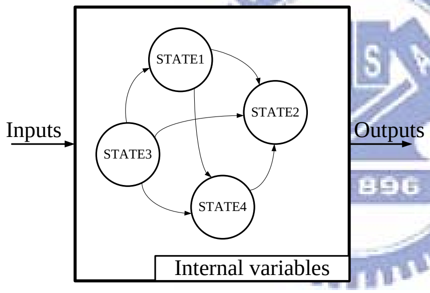


Fig. 2-1 Modularized AFSM module

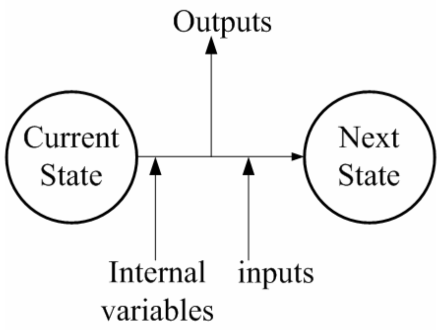


Fig. 2-2 Transition function of AFSM module

2.1.1 Why AFSM?

2.1.1.1 Simple Procedure for Decomposing and Combining

Rodney Brooks thinks that control mechanism of robot resembles animals: A RRCS can be decomposed into some independent components which has independent abilities. These independent components composed of modularized AFSM modules interact with each other, and therefore make up complete abilities for the RRCS. We'll call these independent components *AFSM component* .

Take human beings for example, the brain, hands, legs, and body are independent components. Each component is composed of some parts. For instance, a hand is composed of the skin, muscle, and bones. If we want to construct a human being by the concept of AFSM-based RRCS, the hand will be counted in an AFSM component, and the skin, muscle, and bones will be counted in modularized AFSM modules.

Because each AFSM module is a simple FSM, it can be handled by human being's capability. The simple procedure for decomposing and combining is one of the reasons why we construct a RRCS with AFSM modules. After constructing some modularized AFSM modules, these AFSM modules could connect with each other, and then they will become an independent AFSM component. Finally, a complete RRCS is constructed with some AFSM components. The structure of AFSM component is illustrated with Fig. 2-3.

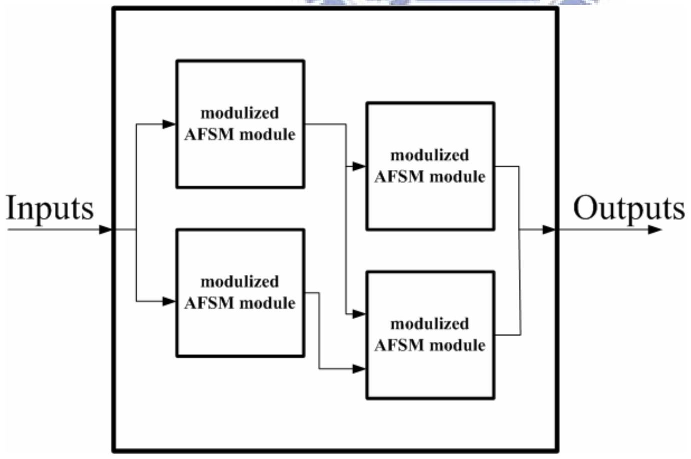


Fig. 2-3 Independent AFSM component

2.1.1.2 Time Discretization

We had explained the purpose of discretization in 1.2, the first step of discretization procedure is *Time Discretization*. In AFSM, time interval between current state and next state is a time unit (T). Therefore, the time of a system is discretized to 1T, 2T, 3T….nT. The event which occurs at continuous time will be shifted to the closest discrete time point.

2.2 Roving Robot Collision Avoidance Experiment

After explaining the concept of AFSM, we will introduce the AFSM-based roving robot collision avoidance experiment [1] in detail.

The experiment had been simulated in [1]. In this work, we want to rebuild it, and check the properties of the behaviors of the AFSM-based RRCS. The implementation of the experiment will be discussed later in Chapter 5.

2.2.1 Experiment Overview

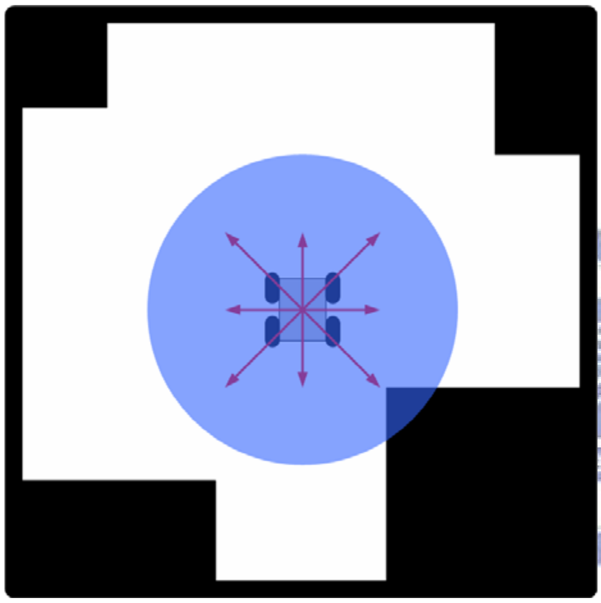


Fig. 2-4 The chart of the experiment

In the experiment, the robot is placed on a two-dimensional environment. The robot has some sonar sensors for detecting the environment, and has a motor for generating force to change its velocity. The motor can generate a force which has 8 kinds of directions, and make the robot move towards 8 kinds of directions which are {U,D,L,R,LU,LD,RU,RD}. The robot is controlled by AFSM-based RRCS, the RRCS monitors the information detected by sonar sensors and then decides to issue what command to motor for changing the robot's velocity.

Whenever the location of robot changes, sonar sensors will detect the environment. If there are some obstacles within *detection range* of sonar sensors, the RRCS will decide new acceleration, velocity and then change the robot's location to avoid collision with the obstacles; if there is no obstacle within detection range, the RRCS will let the robot wander aimlessly around in the environment.

After constructing the AFSM-based RRCS for controlling the robot, we check some properties of the behavior of the robot by OMocha.

2.2.2 Hardware Structure of the Robot

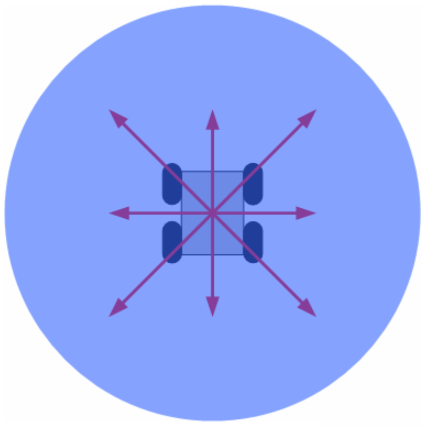


Fig. 2-5 Hardware structure of the robot

2.2.2.1 Sonar Sensors

A sonar sensor has a detection range within a fixed radius. The information detected by sonar sensors will be periodically sent to the AFSM-based RRCS, and then the AFSM-based RRCS can decide whether it issues a command to ask motor to generate a force for avoiding collision with obstacles or not.

2.2.2.2 Motor

The motor of robot continuously wait for a command sent by the AFSM-based RRCS. There are two kinds of commands sent by the AFSM-based RRCS. The first kind of command is “random force” command, the “random force” command asks the motor to generate a force which has random degree and direction, and then the force will generate an acceleration which makes the velocity of the robot to be changed. The second kind of command is “assigned force” command, the “assigned force” command asks the motor to generate a force which has assigned degree and direction. Finally, the “assigned force” command will change the velocity of the robot as well as the “random force” command.

The degree of force generated by motor has a range from 0 to *Max_Force_Degree*, so the acceleration of robot has a range from 0 to *Max_Force_Degree/M* ; moreover, the degree of robot's velocity has a range from 0 to *Max_Velocity_Degree*. Therefore, if the degree of robot's velocity has reached Max_Veloctiy_Degree and then the motor will ignore the "random force" or "assigned force" command which has the same direction as current velocity.

2.2.3 Environment

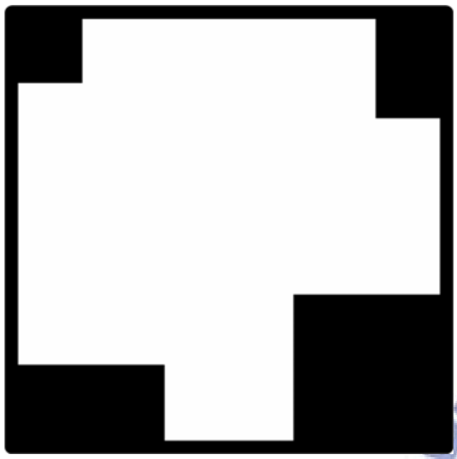


Fig. 2-6 Environment of the experiment

The environment of the experiment is a two-dimensional space. Its shape is rectangle, and has walls on four sides, and has some obstacles on four corners.

2.2.4 Expected Behaviors of the AFSM-based RRCS

The robot which is placed on a two-dimensional environment has two main abilities. The two abilities are sensing obstacles by sonar sensor and moving around by motor. Based on the two abilities provided by robot, the AFSM-based RRCS wants to make the robot achieve two main behaviors：

A. Wander aimlessly keeping to Newton's first and second laws of motion.

B. Make the robot avoid collision with obstacles in environment.

- **How to achieve the two behaviors**

The first behavior can be achieved more easily. The AFSM-based RRCS can periodically issue a command to ask motor to generate a directional force, and the direction and degree of force are generated randomly. According to Newton's second laws of motion, the relationship between force and acceleration is “A=F/M[1]”. Therefore, the force will generate acceleration for the robot, and then the velocity of the robot will be changed. Finally, the robot will move to a new location according to latest velocity.

If the motor generates a force whose degree equals to 0, the robot will keep its original velocity keeping to Newton’s first laws of motion.

After achieving the first behavior, the robot can wander aimlessly, but it can’t avoid collision with obstacles in environment. In order to achieve the second behavior—“avoid collision with obstacles”, the AFSM-based RRCS must monitor the information of the environment detected by sonar sensors. If there is an obstacle in *detection range* of sonar sensors, the AFSM-based RRCS will pass a command to ask motor to generate a force which has a reverse direction of the obstacle, ant then the force will generate a reverse acceleration, finally the robot will gradually keep away from the obstacle. Therefore, the approach can keep the robot to avoid collision with obstacles in environment, and can achieve the second behavior.

2.2.5 Properties To Be Verified

The property we want to check by OMocha is：

Whether the robot will collide with obstacles or walls?

The robot has the two above-mentioned behaviors can wander aimlessly around the environment and try to avoid collision with obstacles. However, the strategy determined by the RRCS for avoiding collision doesn’t guarantee the robot doesn’t collide with obstacles. In the strategy for avoiding collision, the relationship between *“Distance away from the obstacles”* and *“Reverse acceleration”* is the most important part.

In order to make sure the behavior of the strategy is the same as our expected behavior, we must describe the property with Temporal Logic and check whether the strategy really makes the robot not to collide with obstacles. The checking procedure is completed by OMocha.

[1] “M” is the mass of the robot. “F” is the force generated by motor, “A” is the acceleration

Chapter 3
Model Checking for AFSM-based RRCS, Concepts

After introducing AFSM and roving robot collision avoidance experiment, we'll explain how to verify an AFSM-based RRCS by model checker. In this section, we will explain the principle of model checking by the verification procedure of model checker, OMocha [4]. The introduction for OMocha is in Section 3.2.

In Section 3.1.1, we will give two examples for explaining the verification procedure. In the two examples, we will use the formal input language for OMocha. The formal input language for OMocha is explained in detail in Section 3.3.

3.1 Verification Procedure

The concept of verification procedure is step by step to explore *all reachable states* from initial state, and then check whether all explored reachable states which represent the behaviors of programs satisfy the properties.

3.1.1 Two Examples of Verification Procedure

3.1.1.1 Simple Example

Take a simple AFSM-based system shown in Fig. 3-1 as an example. The AFSM-based system is composed of two AFSM modules. The property we want to check is "`AG ((STATE_A=A2 && A_B=false)||(STATE_A=A1 && A_B=true))`". It means whether "`((STATE_A=A2 && A_B=false)||(STATE_A=A1 && A_B=true))`" is always true from initial state to all reachable states.

The definition of initial state is the combination of all variables' initial values of a system. The initial state of the AFSM-based system is { STATE_A=A1 , A_B=false , STATE_B=B1 }. According to the transition functions(update commands) of the AFSM-based system described in programs, the sequential state transition of the AFSM-based system is listed as Table 3-1. The next state of the initial state, which is also the 2nd state of the AFSM system is {STATE_A=A2 , A_B=false , STATE_B=B1 }. Then the next state of the 2nd state, which is also the 3rd state of the AFSM system is { STATE_A=A1 , A_B=true , STATE_B=B1 }. OMocha will keep on exploring the next state of every state. Finally, OMocha will find out that the 2nd to the 5th states are all possible reachable states from the initial state. Then the 6th to the 9th states repeat the value of the 2th to the 5th state, and so on. The all possible states of the system include the initial state and all possible reachable states from the initial state. During the procedure of exploring all possible states of the system, OMocha detects the behaviors of the programs violate the properties at initial state. Therefore, the behaviors of the programs don't satisfy the properties.

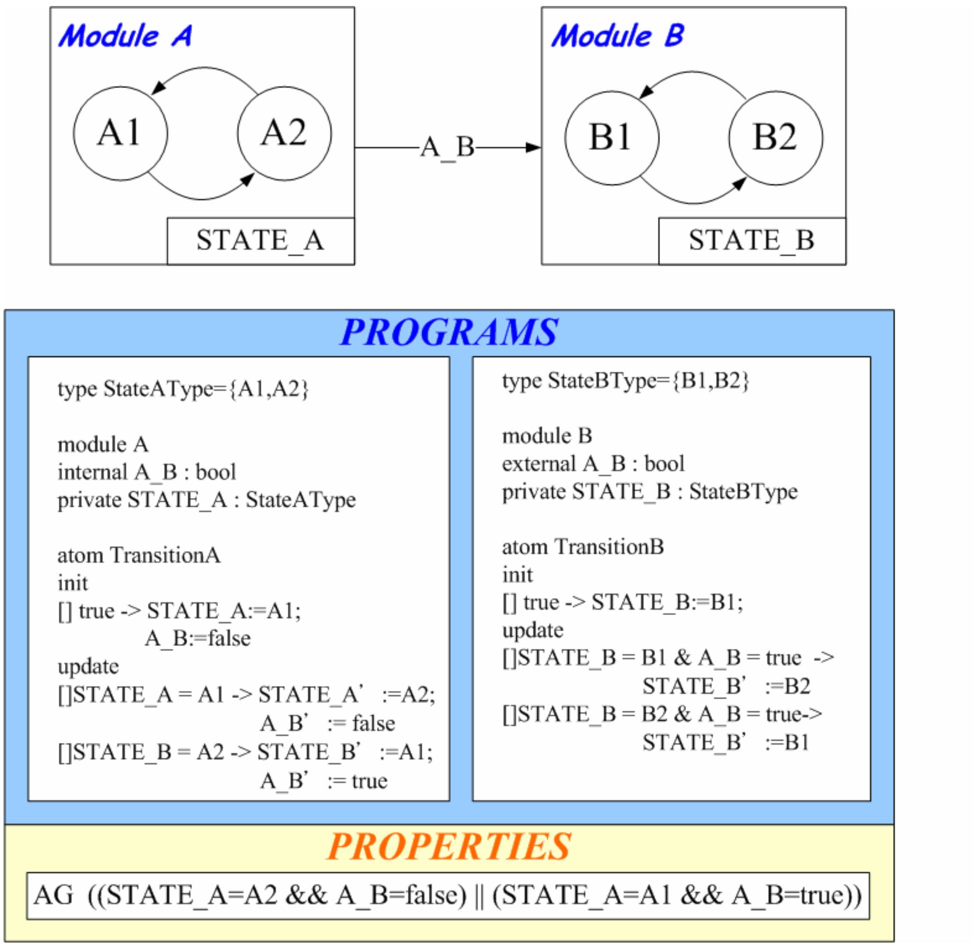
3.1.1.2 Advanced Example

After understanding the simple example of AFSM-based system, let us consider another advanced example. In the advanced example, transition functions (update commands) are allowed to include non-deterministic choices. As shown in Fig. 3-2, module A has a non-deterministic choice as follow:

```
[]STATE_A = A2 -> STATE_A':=A1; A_B':= true
[]STATE_A = A2 -> STATE_A':=A2; A_B':= true
```

If the variables' values of module A are { STATE_A=A2 , A_B=Don't Care } in current state, the variables' values of module A may be { STATE_A=A1,A_B=true } or { STATE_A=A2,A_B=true } in next state. The sequential state transition of the advanced AFSM example is listed as Table 3-2. The non-deterministic choices are provided to system designer for simulating the random situation. In order to make the concept more clearly, we illustrate the *trace-tree of verification procedure* for the advanced example with Fig. 3-3.

In Fig. 2-8, the node which has dotted circle is the state which will determine its next states according to the non-deterministic choices. Therefore, the trace-tree of verification procedure for the advanced example is a multi-branch tree. However, the trace-tree of verification procedure for the simple AFSM example is a single-branch tree as shown in Fig. 3-4.



```
type StateAType={A1,A2}

module A
internal A_B : bool
private STATE_A : StateAType

atom TransitionA
init
[] true -> STATE_A:=A1;
           A_B:=false
update
[]STATE_A = A1 -> STATE_A' :=A2;
                  A_B' := false
[]STATE_B = A2 -> STATE_B' :=A1;
                  A_B' := true
```

```
type StateBType={B1,B2}

module B
external A_B : bool
private STATE_B : StateBType

atom TransitionB
init
[] true -> STATE_B:=B1;
update
[]STATE_B = B1 & A_B = true ->
           STATE_B' :=B2
[]STATE_B = B2 & A_B = true->
           STATE_B' :=B1
```

```
AG ((STATE_A=A2 && A_B=false) || (STATE_A=A1 && A_B=true))
```

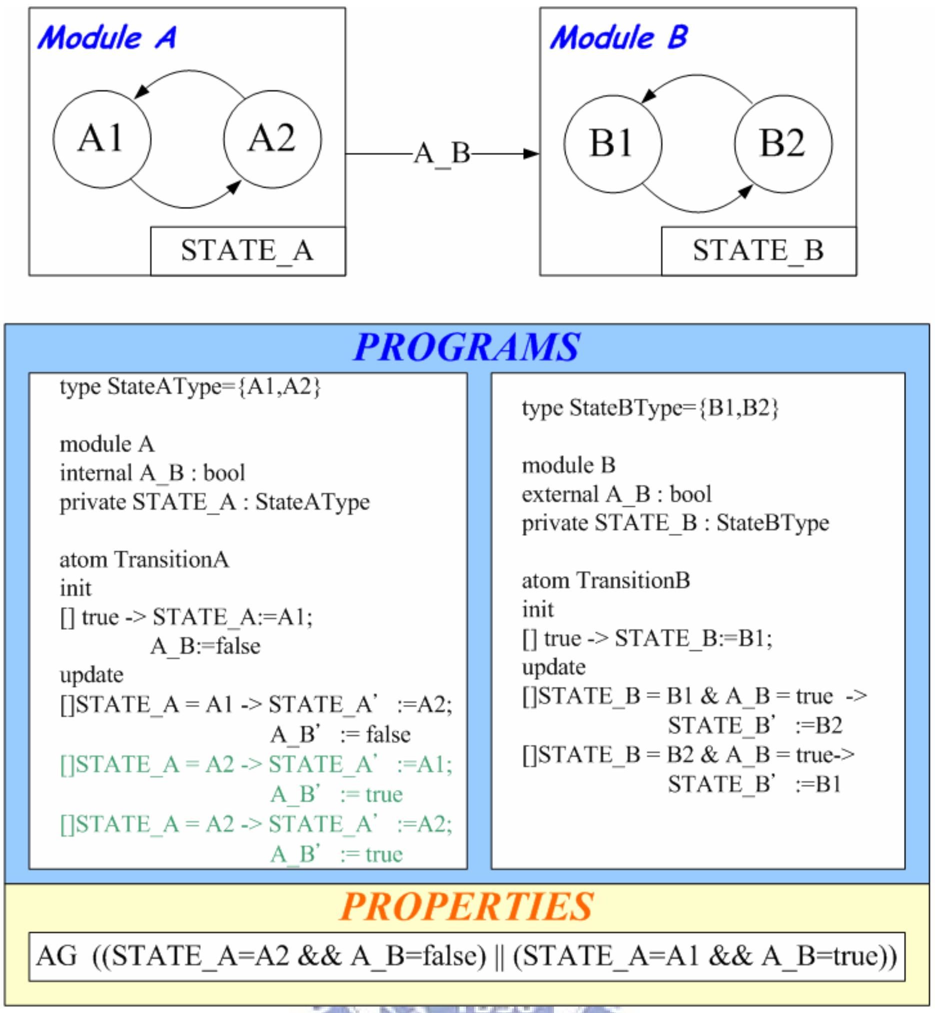
Fig. 3-1. Simple example of AFSM-based system

initial state

all reachable states

state \ variable	STATE_A	A_B	STATE_B
1	A1	False	B1
2	A2	False	B1
3	A1	True	B1
4	A2	False	B2
5	A1	True	B2
6	A2	False	B1
⋮	⋮	⋮	⋮

Table. 3-1. Sequential state transition of simple AFSM-based system



```
type StateAType={A1,A2}

module A
internal A_B : bool
private STATE_A : StateAType

atom TransitionA
init
[] true -> STATE_A:=A1;
            A_B:=false
update
[]STATE_A = A1 -> STATE_A'  :=A2;
                  A_B'  := false
[]STATE_A = A2 -> STATE_A'  :=A1;
                  A_B'  := true
[]STATE_A = A2 -> STATE_A'  :=A2;
                  A_B'  := true
```

```
type StateBType={B1,B2}

module B
external A_B : bool
private STATE_B : StateBType

atom TransitionB
init
[] true -> STATE_B:=B1;
update
[]STATE_B = B1 & A_B = true  ->
                   STATE_B'  :=B2
[]STATE_B = B2 & A_B = true->
                   STATE_B'  :=B1
```

```
AG  ((STATE_A=A2 && A_B=false) || (STATE_A=A1 && A_B=true))
```

Fig. 3-2. Advanced example of AFSM-based system

initial state

all reachable states

variable / state	STATE_A	A_B	STATE_B
1	A1	False	B1
2	A2	False	B1
3	A1	True	B1
4	A2	False	B2
5	A1	True	B2
6	A2	False	B1
7	A2	True	B1
8	A1	True	B2
9	A2	False	B1
⋮	⋮	⋮	⋮

Table. 3-2. Sequential state transitions of advanced AFSM-based system

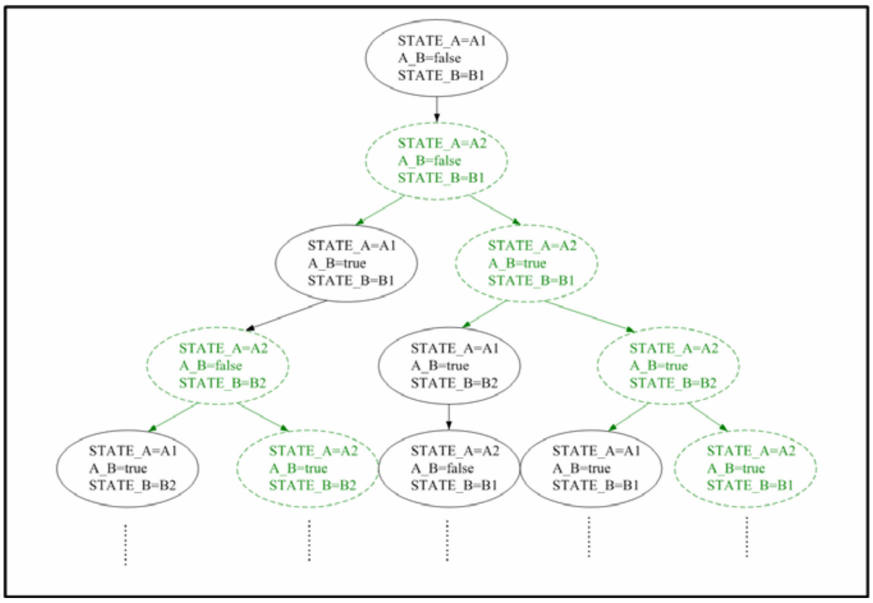


Fig. 3-3

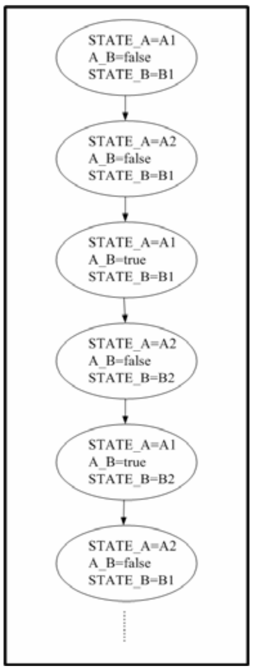


Fig. 3-4

Fig. 3-3. The trace-tree of verification procedure of advanced example. The node which has dotted circle is the state which will determine its next state according to non-deterministic choices.

Fig. 3-4. The trace-tree of verification procedure of simple example

3.2 Model Checker：OMocha

The model checker chosen for our research is *OMocha [4]*. The formal input language for OMocha includes two parts: The first part is *programs* described by *UNITY-based specification language [2]*, and the second part is *properties* described by *Temporal Logic [5]*. After the formal input language is fed into OMocha, OMocha will check whether the behaviors of the programs satisfy the properties. If the behaviors of the programs violate the properties, OMocha will show one counterexample. Otherwise, it’ll show the behaviors of the programs satisfy the properties.

. In Section 3.3, we’ll introduce the formal input language for OMocha.

3.3 Formal Input Language for OMocha

3.3.1 Programs Described by UNITY-based Specification Language

(A) Introduction

In OMocha, the programs are described by UNITY-based specification language. There are two main reasons about why it uses UNITY to describe the programs as follows：

(1) UNITY could represent the relationship between current state and next state, what is called transition function. Therefore, we could describe an AFSM-based RRCS by UNITY.

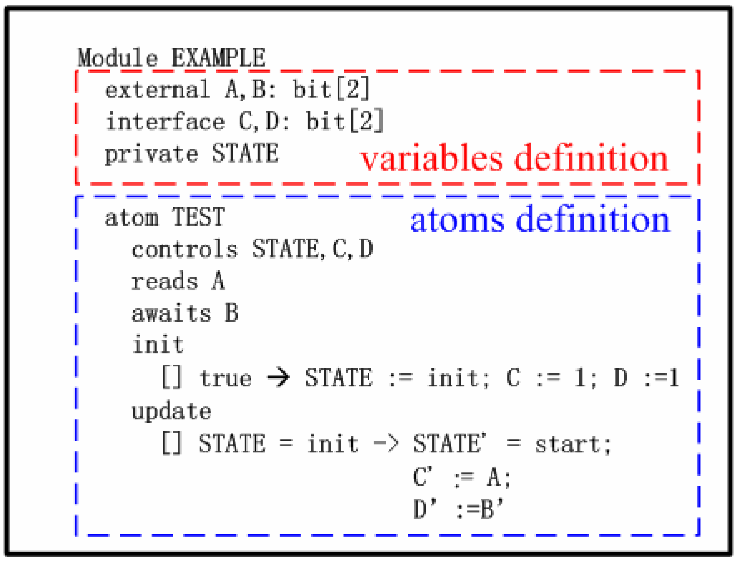
(2) In order to operation in coordination with OMocha. In OMocha, the only data types can be defined are cyclic integer and boolean, and the syntax and semantics of UNITY can provide cyclic integer (e.g., “`A: bit[5]`”, the range of cyclic integer A is from 0 to 31).

(B) Syntax and Semantics

There are two parts in programs:

(1)Module Description

In the first part of programs, we describe all AFSM modules in *module description*. For describing a module, it includes two necessary parts: *variables definition* and *atoms definition*.



```
Module EXAMPLE
  external A,B: bit[2]
  interface C,D: bit[2]
  private STATE

  atom TEST
    controls STATE,C,D
    reads A
    awaits B
    init
      [] true → STATE := init; C := 1; D :=1
    update
      [] STATE = init -> STATE' = start;
                         C' := A;
                         D' :=B'
```

variables definition
atoms definition

Fig. 3-5. Module description

Variables Definition

In variables definition, there are three kinds of variables can be defined: *external*, *interface*, and *private*.

***External variables*-------**The input ports of AFSM module, they receive data from other AFSM modules' interface variables.

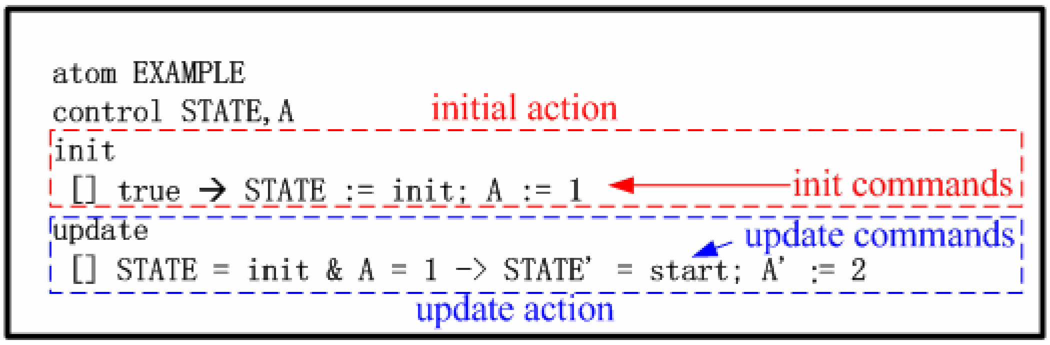
***Interface variables*-------**The output ports of AFSM module, they send data to other AFSM modules' external variables.

***Private variables*-------**The local variables of AFSM module, they don't connect with other AFSM modules.

Three kinds of data types which can be defined for above three kinds of variables are "cyclic integer", "boolean" and "enum".

Atoms Definition

In atoms definition, we describe the *init action* executed during initial round, and the *update action* executed during each update round. The initial and update action are specified by the keywords **`init`** and **`update`**. There are some *init commands* in initial action, and there are some *update commands* in update action. An example for atoms definition is shown as Fig. 3-6.



```
atom EXAMPLE
control STATE, A
init
 [] true → STATE := init; A := 1
update
 [] STATE = init & A = 1 -> STATE' = start; A' := 2
```

Fig. 3-6. Example for atoms definition

In each update round, every variable x has two values. The value of x at the beginning of the round is called the *latched value*, and the value of x at the end of the round is called the *updated value*. We use unprimed symbols, such as **x**, to refer to latched values, and primed symbols, such as **x′**, to refer to the corresponding updated values.

The updated value of (N-1)th round is equal to the latched value of Nth round. The latched value of x is also the current state of x, and the updated value of x is also the next state of x. The relationship between latched value (current state) and updated value (next state) during neighbor update rounds is shown as Fig. 3-7.

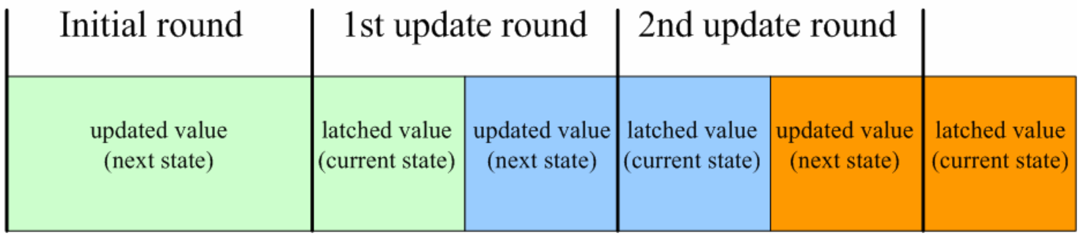

Initial round
1st update round
2nd update round
updated value (next state)
latched value (current state)
updated value (next state)
latched value (current state)
updated value (next state)
latched value (current state)

Fig. 3-7. The relationship between latched value and updated value during neighbor update rounds.

Let us look the example shown in Fig. 3-6, the updated value of STATE and A are init and 1 at initial round. According to the update command in update action, if the latched value of STATE and A are init and 1, the updated value of them will be set to start and 2. Therefore, the updated values of STATE and A are start and 2 at 1st update round. Update commands which determine the relationship between latched values and updated values, can regard as transition functions which determine relationship between current state and next state.

(2) Module Connection

After all AFSM modules are described in module description, we need to describe the connection relationship between these AFSM modules. An interface variable can connect with some external variables of other AFSM modules which have the same name as the interface variable. An external variable can only connect with an interface variable of another AFSM module which has the same name as the external variable.

3.3.2 Properties Described by Temporal Logic

(A) Introduction

In OMocha, the method chosen to describe the properties of an AFSM-based RRCS is *Temporal Logic*.

Temporal Logic is used to represent the properties of state transitions of a system over time domain. For instance, we want to check whether variable A is always less than 10 during all possible states. In this case, the representation of Temporal Logic is “AG A<10”, the meaning of ”AG” is “always true” during all possible states from initial state. After describing the programs of an AFSM-based RRCS by UNITY, we can describe the properties of the AFSM-based RRCS by Temporal Logic, and the properties are what we want to check by OMocha. When OMocha receives the formal input language including programs and properties, it can check whether the behaviors of the programs satisfy the properties.

(B) Syntax and Semantics

Every property of a system is described by Temporal Logic. A Temporal Logic formula consists of *the propositional logic formula* and *temporal connectives*： *The propositional logic formulas* are expressions which consist of logical operators and the variables of the system. *The temporal connectives* are expressions to indicate the subset of future states of the system.

The temporal connectives are pairs of symbols：

The first member of the pair is one of

A - meaning on all paths from the “current” state, read as “inevitably”

E - meaning on at least one path from the ”current” state, read as “possibly”

The second member of the pair is one of

X - meaning the next state

G - meaning all future states, read as “globally”

F - meaning some future state

U - meaning until

Take “mutual exclusion” as example. Suppose we are talking about two processes P1, P2 that share data. The protocol allows only one process to be in its critical section at any time.

If we want to describe the “mutual exclusion” property by Temporal Logic, the Temporal Logic formula will be described as follow：

```
AG !( Critical[P1] & Critical[P2] )
```

The propositional logic formula	!(Critical[P1] & Critical[P2])
The temporal connectives	AG

This Temporal Logic formula is true iff `Critical[P1]` and `Critical[P2]` won’t be true in the meantime for all states on all paths into the future from current state.

Chapter 4
Model Checking for AFSM-based RRCS, Approaches

In this Chapter, we present three approaches to lower the difficulty of formal verification for the experiment. After using the three approaches to reduce the number of states of the RRCS and environment, formal verification can become applicable for the experiment.

4.1 State Space Discretization

A system described on the continuous domain can't be verified by OMocha, because the number of all possible states is infinite. Before constructing an AFSM-based RRCS we must transform the system and environment from continuous domain to discrete domain. Otherwise, OMocha can't handle it.

In discretization procedure, there are two parts. (1) Time Discretization, and (2) Space Discretization. Time Discretization has been explained in Section 2.1.1.2, therefore we will only explain Space Discretization in this section. We will give two examples to illustrate the relationship between continuous space and discrete space below.

Take a simple MAP as first example, the continuous MAP whose size is 2*2 m^2 is transformed into a discrete MAP. In x-axis and y-axis, the continuous domain is partitioned into 21 points separately (x-axis:0.1.2….20, y-axis:0.1.2….20). Therefore, the distance between two neighbor points is 0.1m, and the size of the discrete MAP is 21*21. The relationship between continuous and discrete MAP is shown as Fig. 4-1.

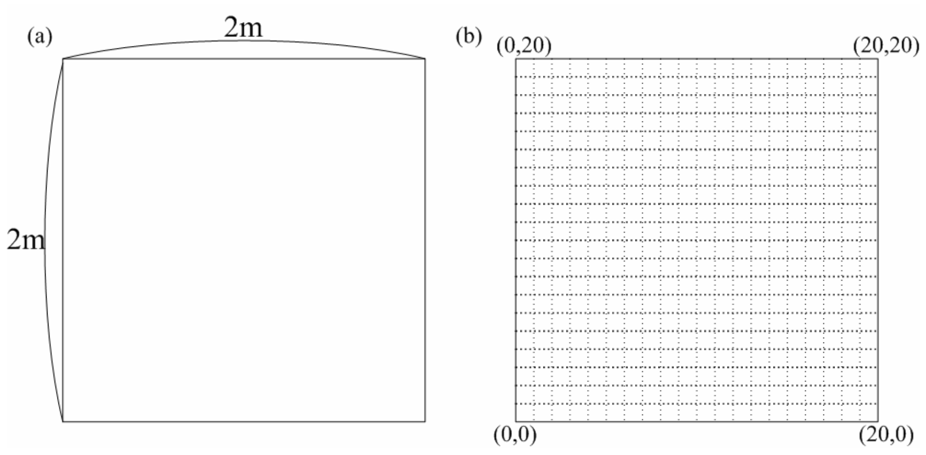


Fig. 4-1. (a) continuous MAP (b) discrete MAP

Then, we give another example. In Section 2.2.5, we have mentioned that in the strategy for avoiding collision, the relationship between “Distance away from the obstacles” and “Reverse acceleration” is the most important part. In Fig. 4-2, we illustrate the relationship between continuous domain and discrete domain in this example.

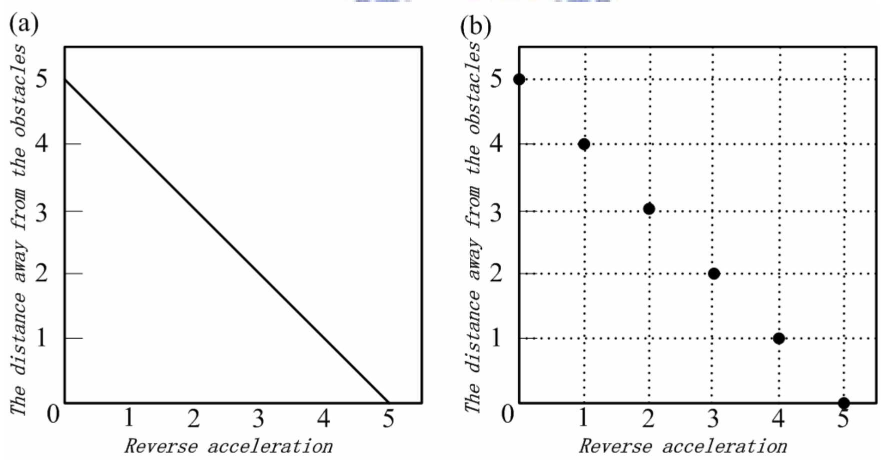


Fig. 4-2 (a) continuous domain (b) discrete domain

In Fig. 4-2, “Reverse acceleration” is approximately linear inverse proportion to “Distance away from the obstacles” on continuous domain, the curve presents the relationship between the two parameters. The number of all possible mapping relations of them is infinite, the mapping set includes { (0, 5)..(0.5,4.5)..(3.5,1.5)..(5,0) }. After transformation, the mapping set has only fix points on discrete domain, they are { (0,5) . (1,4) . (2,3) . (3,2) . (4,1) . (5,0) }.

After *discretization procedure*, the complexity of a system will be simplified to the degree can be handled by OMocha.

4.2 External Function for Computation/State Hiding

In order to improve the capabilities which the UNITY-based programs can support, and reduce the number of states of a system. OMocha provides the ***external function*** for system designer. The two main advantages are listed below：

4.2.1 Computation Hiding

The semantics and syntax of UNITY are very basic and aren’t as powerful as high-level language. For this reason, it’ll be very hard to build complicated programs of a system by UNITY.

In order to improve the capabilities which the UNITY-based programs can support, OMocha provides the external function for system designer. The external function is described by C language. The UNITY which includes external function is called *advanced UNITY.*

In original UNITY, the semantics and syntax can only provide basic capabilities, these basic capabilities include：

Value assignment

Basic logic operations: and/or/not/invert

Basic arithmetic operations: addition/subtraction

Basic comparison operators: > <

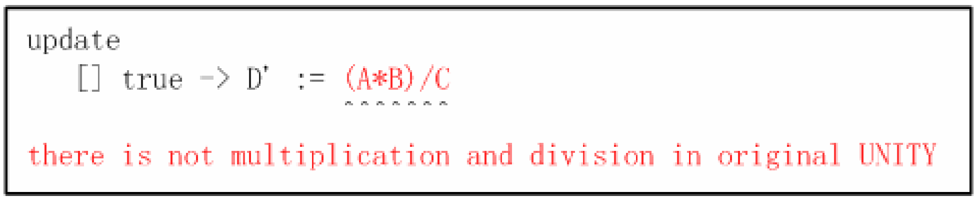
Non-nested if-then-else structure

……etc

In advanced UNITY, we can pass variables into external functions, and then receive the return value of external function by variables which defined in UNITY.

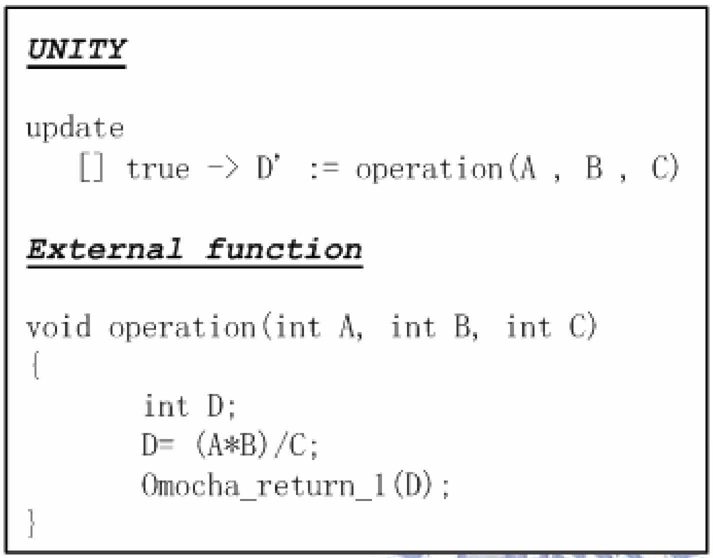
There are two examples for explaining computation hiding through external function. The two example are listed below：

Example 1



```
update
    [] true -> D'  := (A*B)/C
                      ^^^^^^^^

there is not multiplication and division in original UNITY
```

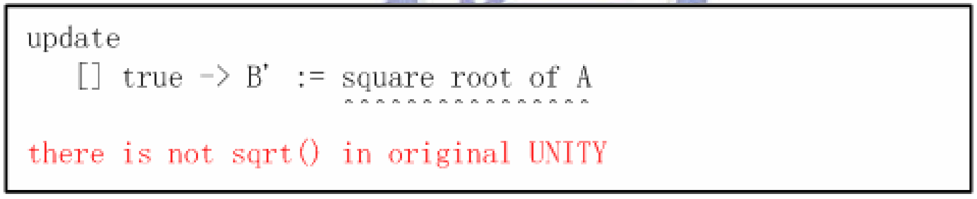
A part of programs described with original UNITY



```
UNITY

update
    [] true -> D'  := operation(A , B , C)

External function

void operation(int A,  int B,  int C)
{
         int D;
         D= (A*B)/C;
         Omocha_return_1(D);
}
```

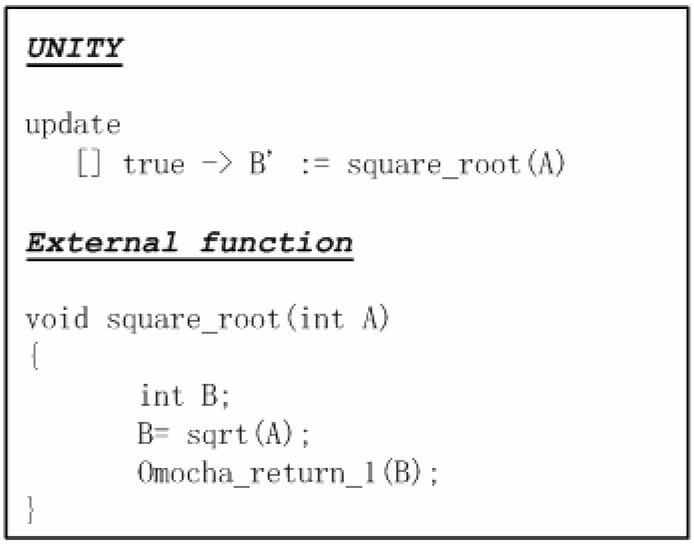
The same part described with advanced UNITY

Example 2



```
update
    [] true -> B'  := square root of A
                      ^^^^^^^^^^^^^^^^

there is not sqrt() in original UNITY
```

A part of programs described with original UNITY



```
UNITY

update
    [] true -> B'  := square_root(A)

External function

void square_root(int A)
{
         int B;
         B= sqrt(A);
         Omocha_return_1(B);
}
```

The same part described with advanced UNITY

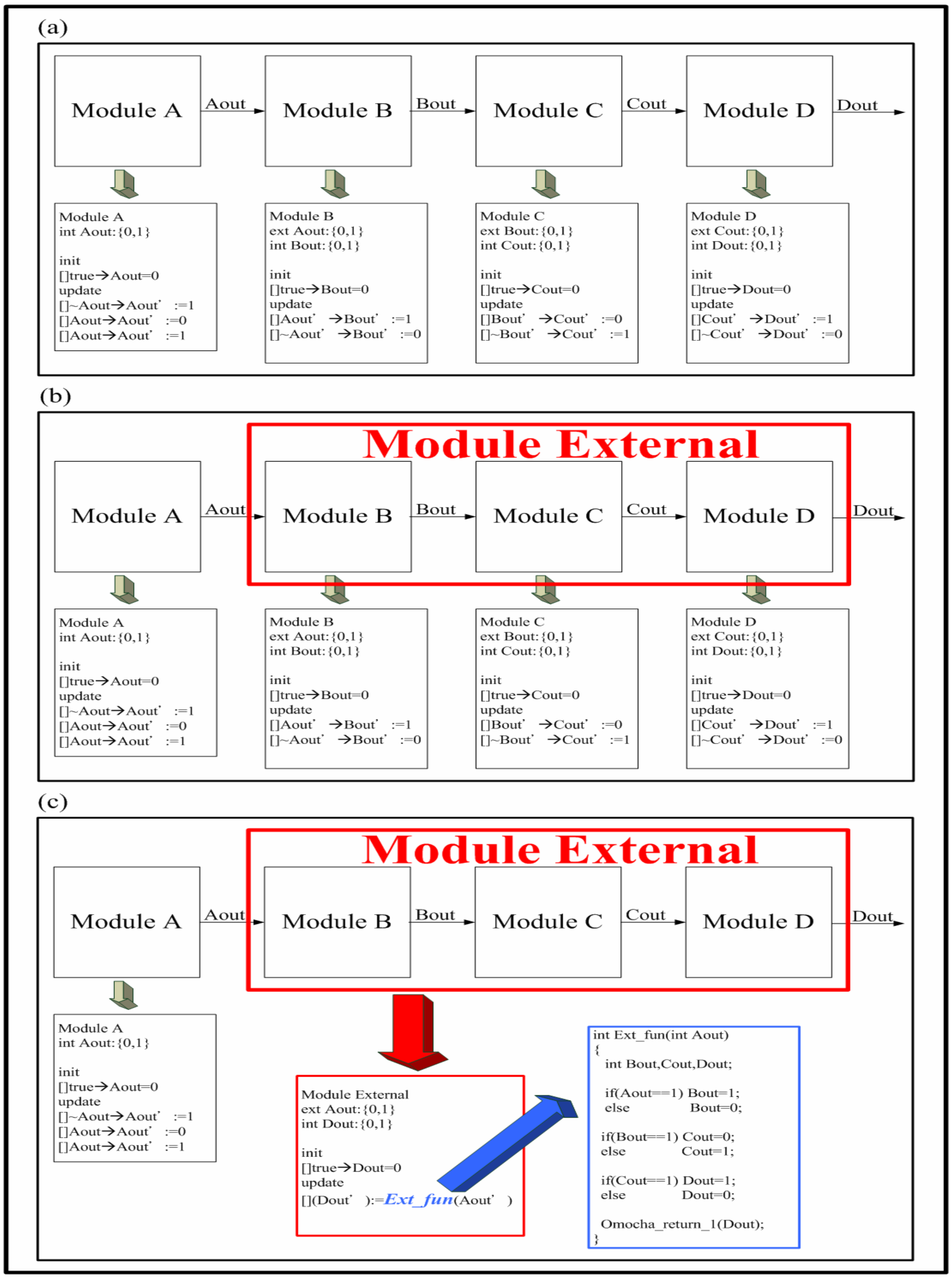
4.2.2 State Hiding：Reducing the Number of All Reachable States of a System

How complicated a system can be verified by OMocha depends on the number of all reachable states. Once the number of all reachable states of a system is greater than the limitation of OMocha's capability, the "out of memory" problem will occur during checking procedure. Therefore, we have to carefully control the complexity of a system so that the resource (memory, CPU speed...etc) of OMocha can handle the checking procedure.

The number of all reachable states of a system depends on the all possible combination of all variables which are defined in UNITY-based programs. If we can move out some variables which are defined in UNITY-based programs, and encapsulate them into external function, the number of all reachable states will reduce.

But, what kinds of variables can be encapsulated into external function？ During verification procedure, there are some system variables which are irrelevant to behavior verification. For example, in the experiment explained in Chapter 2, OMocha only needs to know the velocity and location of the robot whereas it doesn't need to know the computation of detecting environment, and determining the degree of acceleration. The variables for detecting environment and determining the degree of acceleration can be exported to external function.

An example of the encapsulation procedure of external function is shown as Fig. 4-3. In Fig. 4-3, the system is composed of four AFSM modules. There is one interface variable in each module, so the total number of the variables in the system is four. According to encapsulation principle, if a module doesn't include some nondeterministic update commands, it can be encapsulated into a external module. Take the system as a example, the module B, module C and module D can be encapsulated into a external module which invokes a external function to handle all update commands of them, the encapsulation procedure shown as Fig 4-3(c). The module A can not be encapsulated into the same external module, because it includes one nondeterministic update command. After encapsulation procedure, the system reduces the number of modules from 4 to 2, and reduces the number of variables from 4 to 2. The two interface variables Bout,Cout are encapsulated into the external function "Ext_fun", so model checker doesn't need to consider them. In some cases, reducing the number of variables by encapsulation procedure can obviously lower the number of all reachable states of the system and lower the running time of checking procedure, especially in a complicated system.



```
Module A
int Aout:{0,1}

init
[]true→Aout=0
update
[]~Aout→Aout' :=1
[]Aout→Aout' :=0
[]Aout→Aout' :=1
```

```
Module B
ext Aout:{0,1}
int Bout:{0,1}

init
[]true→Bout=0
update
[]Aout' →Bout' :=1
[]~Aout' →Bout' :=0
```

```
Module C
ext Bout:{0,1}
int Cout:{0,1}

init
[]true→Cout=0
update
[]Bout' →Cout' :=0
[]~Bout' →Cout' :=1
```

```
Module D
ext Cout:{0,1}
int Dout:{0,1}

init
[]true→Dout=0
update
[]Cout' →Dout' :=1
[]~Cout' →Dout' :=0
```

```
Module A
int Aout:{0,1}

init
[]true→Aout=0
update
[]~Aout→Aout' :=1
[]Aout→Aout' :=0
[]Aout→Aout' :=1
```

```
Module B
ext Aout:{0,1}
int Bout:{0,1}

init
[]true→Bout=0
update
[]Aout' →Bout' :=1
[]~Aout' →Bout' :=0
```

```
Module C
ext Bout:{0,1}
int Cout:{0,1}

init
[]true→Cout=0
update
[]Bout' →Cout' :=0
[]~Bout' →Cout' :=1
```

```
Module D
ext Cout:{0,1}
int Dout:{0,1}

init
[]true→Dout=0
update
[]Cout' →Dout' :=1
[]~Cout' →Dout' :=0
```

```
Module A
int Aout:{0,1}

init
[]true→Aout=0
update
[]~Aout→Aout' :=1
[]Aout→Aout' :=0
[]Aout→Aout' :=1
```

```
Module External
ext Aout:{0,1}
int Dout:{0,1}

init
[]true→Dout=0
update
[](Dout' ):=Ext_fun(Aout' )
```

```
int Ext_fun(int Aout)
{
  int Bout,Cout,Dout;

  if(Aout==1) Bout=1;
  else        Bout=0;

 if(Bout==1) Cout=0;
 else        Cout=1;

 if(Cout==1) Dout=1;
 else        Dout=0;

 Omocha_return_1(Dout);
}
```

Fig. 4-3. Encapsulation procedure

(a) A system is composed of four AFSM modules

(b) The module B, module C and module D can be encapsulated into a external module

(c) The three modules will be integrated into one external module, the UNITY-based programs of the external module and C code of external function `Ext_fun()` are shown in the figure.

4.3 Elimination of Unnecessary Checking Cases

The concept of verification procedure is step by step to explore *all reachable states* from initial state. Therefore this is a kind of method of exhaustion. However, according to the properties we want to check by OMocha, we can eliminate some unnecessary checking cases, because this part of checking cases will never violate the properties. Take the experiment explained in Chapter 2 as example. The robot will never collide with obstacles while it wanders aimlessly in the range which has no obstacles. Therefore, OMocha can eliminate the part of checking cases.

Chapter 5
Implementation of Roving Robot Collision Avoidance Experiment

In this Chapter, we will present how to construct the AFSM-based RRCS and environment in the experiment with UNITY, and explain the AFSM-based RRCS in detail.

We have explained the chart of an AFSM module in Section 2.1, and explained how to describe the programs of an AFSM module has explained in Section 3.3.1. These two sections are the most important foundations for this section.

In Section 5.1, we will show the full structure of the experiment, and then briefly introduce these AFSM modules in the experiment. In Section 5.2, we introduce every AFSM module in detail, and how these AFMS modules connect with other modules and work in coordination. In Section 5.3, we explain the "No_Collision" property described by Temporal Logic. The checking results of the experiment are explained in Chapter 6.

5.1 Full Structure of the Experiment

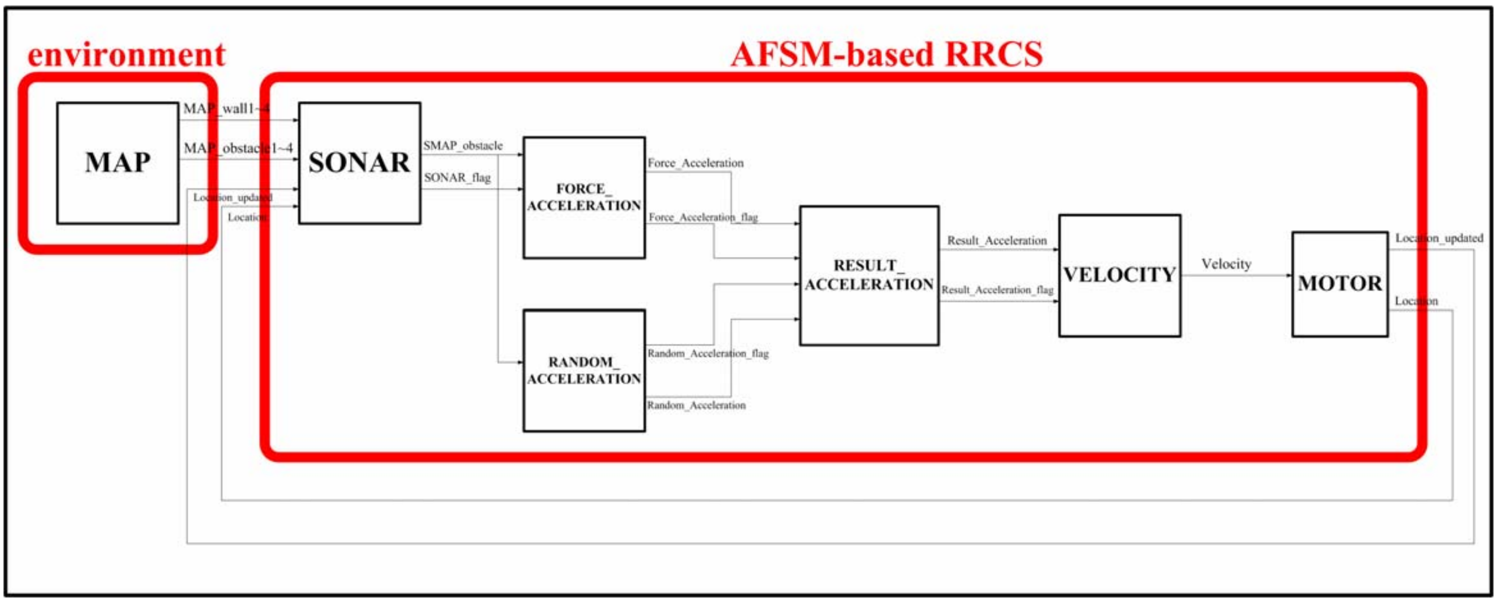
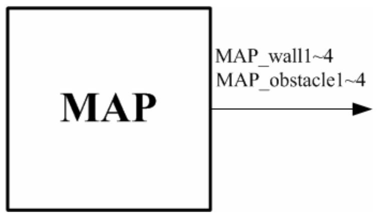
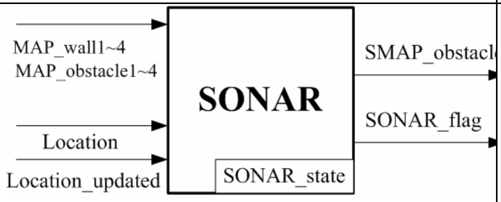
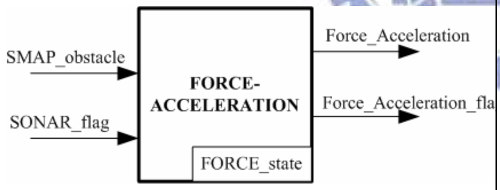
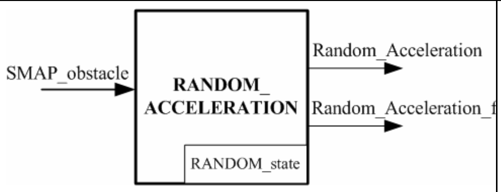


Fig. 5-1 Full structure of the experiment

The full structure of the experiment is shown as Fig. 5-1, the AFSM-based RRCS is composed of 6 AFSM modules, and environment is composed of 1 AFSM module. These modules are listed in Table 5-1：

Module name	***Module figure***	***Functionality***
MAP		● Set the position of obstacles and walls into `MAP_walls` and `MAP_obstacles` at initial round. ● Provide the map of environment to other modules through interface variable
SONAR	 MAP_wall1~4 MAP_obstacle1~4 Location Location_updated SONAR SONAR_state SMAP_obstacl SONAR_flag	● In each round, SONAR reads `Location_updated` from MOTOR module, and then SONAR detects the environment and produces the robot centered map of obstacles and walls ● Provide the robot centered map stored in `SMAP_obstacle` to FORCE_ACCELERATION and RANDOM_ACCELERATION modules.
FORCE_ ACCELERATION	 SMAP_obstacle SONAR_flag FORCE-ACCELERATION FORCE_state Force_Acceleration Force_Acceleration_fla	● In each round, FORCE_ACCELERATION awaits robot centered map of obstacles from SONAR module, and then compute `Force_Acceleration` for RESULT_ACCELERATION module
RANDOM_ ACCELERATION	 SMAP_obstacle RANDOM_ ACCELERATION RANDOM_state Random_Acceleration Random_Acceleration_f	● In each round, If there is no any obstacle in detection range(the updated value of `SMAP_obstacle` is {(0,0),LU}), RANDOM_ACCELERATION module produces a random `Random_Acceleration` for RESULT_ACCELERATION module.

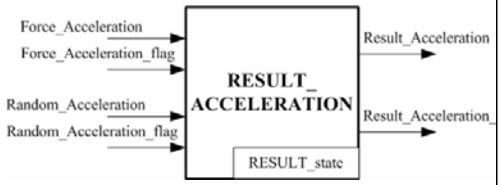
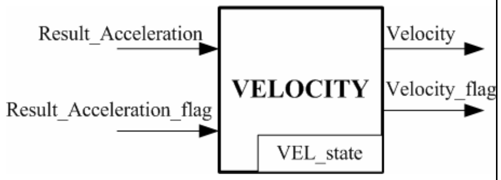
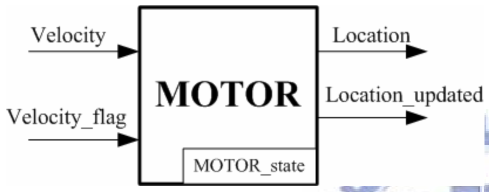
RESULT_ ACCELERATION	 Force_Acceleration Force_Acceleration_flag Random_Acceleration Random_Acceleration_flag RESULT_ ACCELERATION RESULT_state Result_Acceleration Result_Acceleration_	● In each round, RESULT_ACCELERATION awaits `Force_Acceleration` and `Random_Acceleration`, and determine which one to output as `Result_Acceleration` for VELOCITY module
VELOCITY	 Result_Acceleration Result_Acceleration_flag VELOCITY VEL_state Velocity Velocity_flag	● In each round, VELOCITY awaits `Result_Acceleration` from RESULT_ACCELERATION, and then update `Velocity`.
MOTOR	 Velocity Velocity_flag MOTOR MOTOR_state Location Location_updated	● In each round, MOTOR awaits `Velocity` from VELOCITY, and then update `Location`. ● Set `Location_updated` to true while updated value of `Location` isn't equal to latched value of `Location`

Table 5-1 Brief introduction for 7 AFSM modules

5.2 Introduction for each AFSM Module in detail

1. MAP:

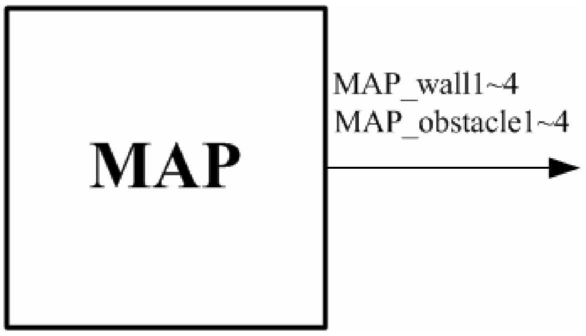
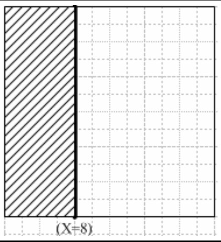
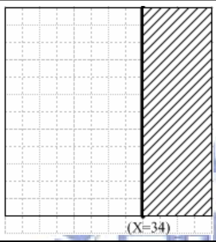
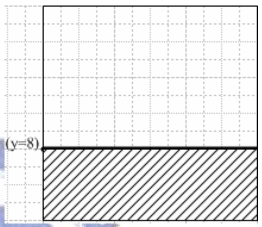
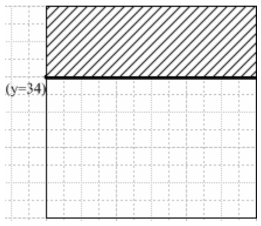


Fig. 5-2 MAP module

As shown in Table 5-1, MAP module has two functionalities:

- Set the position of obstacles and walls into `MAP_walls` and `MAP_obstacles` at initial round.
- Provide the map of environment to other modules through interface variable

The MAP module is for simulating the environment. In MAP module, we set the position of obstacles and walls in environment map at initial round. The representation of obstacle or wall is **{ *position* , *direction* }**. The ***position*** is represented by (position of X-axis ,position of Y-axis), and the ***direction*** includes four kinds of directions, which are {LU(left-up),LD(left-down),RU(right-up),RD(right-down)}. In Fig. 5-3, we list some examples to illustrate the usage of the representation.

Example of wall				
Representation	**{ (8,0),LU/LD }**	**{ (34,0),RU/RD }**	**{ (0,8),LD/RD }**	**{ (0,34),LU/RU }**

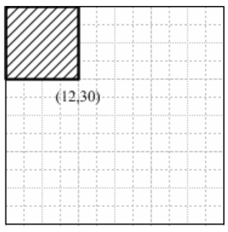
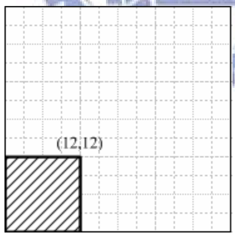
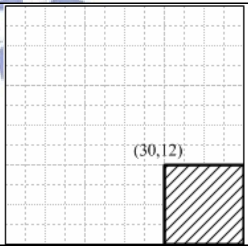
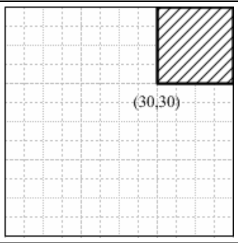
Example of obstacle				
Representation	**{ (12,30) , LU }**	**{ (12,12) , LD }**	**{ (30,12) , RD }**	**{ (30,30) , RU }**

Fig. 5-3 Some examples for the representation of `MAP_obstacle`/`MAP_wall`

Take the MAP1.0 shown in Fig. 5-4 as example of environment. The position of walls are { (8,0)} , LU } , { (38,0), RU } , { (0,8) , LD } , { (0,38) , RU }, and the position of obstacles are { (12,12) ,LD },{ (34,12) , RD },{ (12,34) , LU },{ (34,34) , RU }. According to the representation, we can set the values of `MAP_obstacles` and `MAP_walls`. The ***interface variables*** `MAP_obstacles` and `MAP_walls` will be sent to SONAR module.

The introduction for all variables in MAP module is shown as Table 5-2, the interface variables `MAP_obstacle1-4` and `MAP_wall1-4` will connect to SONAR module for informing the map of environment.

The figure and features of MAP1.0 is shown as Fig 5-4. The MAP 1.0 is very simple. It is a two-dimensional square whose size is 30*30, and the obstacles can only expand from 4 corners. Because there is only "unsigned ranged integer" data type in OMocha, we reserve the boundary buffer area around the environment. The reason is in order to avoid the appearance of negative integer in intermediate results during operations.

Interface	***Send to***	***Functionality***
`MAP_wall1~4`	SONAR	The position of the walls
`MAP_obstacle1~4`	SONAR	The position of the obstacles
Private		***Functionality***
`MAP_state`		Store current state of MAP

Table 5-2　All variables in MAP module

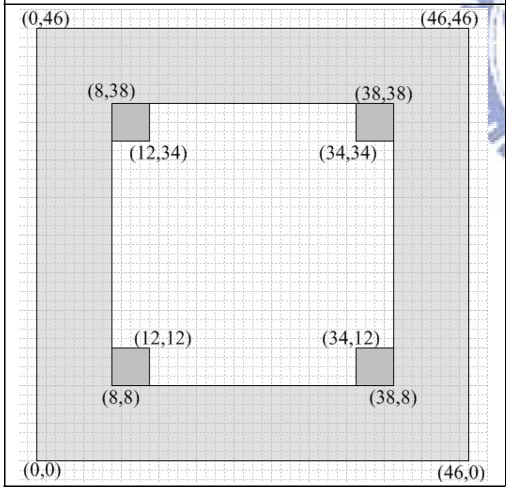
MAP 1.0	***Features of MAP1.0***
 (0,46) (46,46) (8,38) (38,38) (12,34) (34,34) (12,12) (34,12) (8,8) (38,8) (0,0) (46,0)	● Map size: 30 x 30 (from (8,8) to (38,38)) ● Width of boundary buffer area: 8 ● The obstacles can only expand from 4 corners

Fig. 5-4　MAP 1.0

Comment for UNITY fragment of MAP

```
init
    [] true ->  MAP_wall1_X:= 6'b001000; MAP_wall1_Y:=6'b000000; MAP_wall1_type:=LU;  -- { (8,0) , LU }
               MAP_wall2_X:= 6'b100110; MAP_wall2_Y:=6'b000000; MAP_wall2_type:=RU;  -- { (38,0) , RU }
               MAP_wall3_X:= 6'b000000; MAP_wall3_Y:=6'b001000; MAP_wall3_type:=LD;  --{ (0,8) , LD }
               MAP_wall4_X:= 6'b000000; MAP_wall4_Y:=6'b100110; MAP_wall4_type:=LU;  --{ (0,38) , LU }
               MAP_obstacle1_X:= 6'b001100; MAP_obstacle1_Y:=6'b100010; MAP_obstacle1_type:=LU;  -- { (12,34) , LU }
               MAP_obstacle2_X:= 6'b100010; MAP_obstacle2_Y:=6'b100010; MAP_obstacle2_type:=RU; -- { (34,34) , RU }
               MAP_obstacle3_X:= 6'b100010; MAP_obstacle3_Y:=6'b001100; MAP_obstacle3_type:=RD; -- { (34,12) , RD }
               MAP_obstacle4_X:= 6'b001100; MAP_obstacle4_Y:=6'b001100; MAP_obstacle4_type:=LD  -- { (12,12) , LD }
```

Fig. 5-5 UNITY fragment of MAP：　Set position of walls and obstacles at initial round

In the UNITY fragment of MAP shown as Fig. 5-5, we set position of walls and obstacles into `MAP_obstacles` and `MAP_walls`.

Line 1： The initial action of atoms is specified by the keywords **`init`.**

Line 2-9： Set the value of `MAP_obstacles` and `MAP_walls`.

Line 4： The position of `MAP_wall3` is (0, 8), and the direction is LD.

2. SONAR：

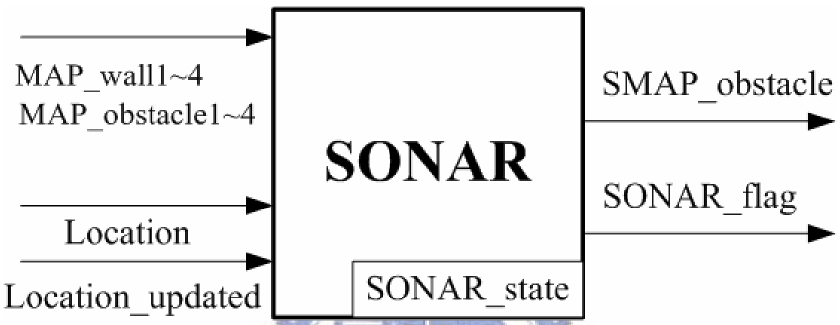


Fig. 5-6 SONAR module

As shown in Table 5-1, SONAR module has two functionalities：

- In each round, SONAR reads `Location_updated` flag from MOTOR module, and then SONAR detects the environment and produces the robot centered map of obstacles and walls
- Provide the robot centered map stored in SMAP_obstacle to FORCE_ACCELERATION and RANDOM_ACCELERATION modules.

SONAR module is the module to simulate the behavior of sonar sensor on the robot. It receives the map of environment from MAP module and location of robot from MOTOR module. After receiving above external variables from MAP and MOTOR module, SONAR module will produce a robot centered map of obstacles and walls according to the detection range of sonar sensor. The detection range of sonar sensor is a robot centered range whose size is 16x16, and for every quadrant the size is 8x8. The figure of detection range is shown as Fig. 5-7.

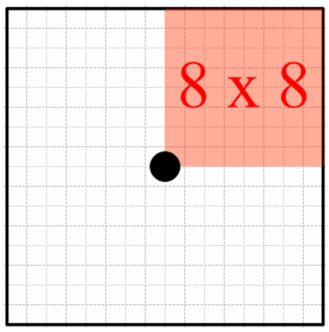
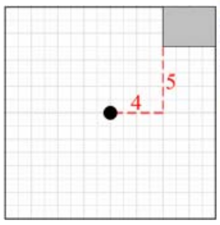
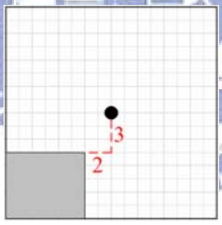
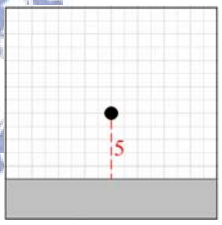
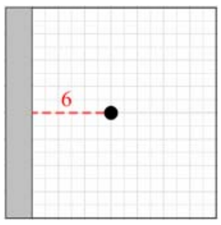


Fig. 5-7 Detection range

The information of the robot centered map of obstacles and walls is stored in the interface variable `SMAP_obstacle`, and the `SMAP_obstacle` will be sent to FORCE_ACCELERATION and RANDOM_ACCELERATION modules.

The representation of `SMAP_obstacle` is **{ *distance* ,*direction* }**, the ***distance*** in the representation are represented with the distance away from the obstacle or wall for X-axis and Y-axis separately. In Fig. 5-8, we list some examples to illustrate the usage of the representation for `SMAP_obstacle`.

Example				
representation	**{(4,5),RU}**	**{(2,3),LD}**	**{(0,5),LD/RD}**	**{(6,0),LU/LD}**

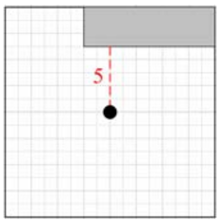
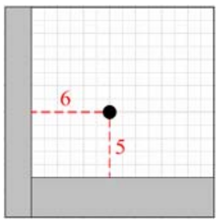
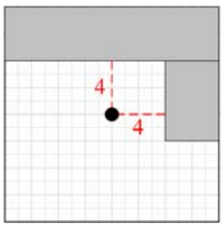
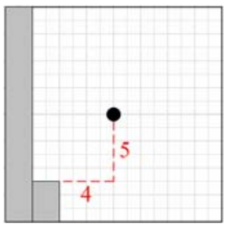
Example				
representation	**{(0,5),RU}**	**{(6,5),LD}**	**{(4,4),RU}**	**{(4,5),LD}**

Fig. 5-8. Some examples for the representation of `SMAP_obstacle`

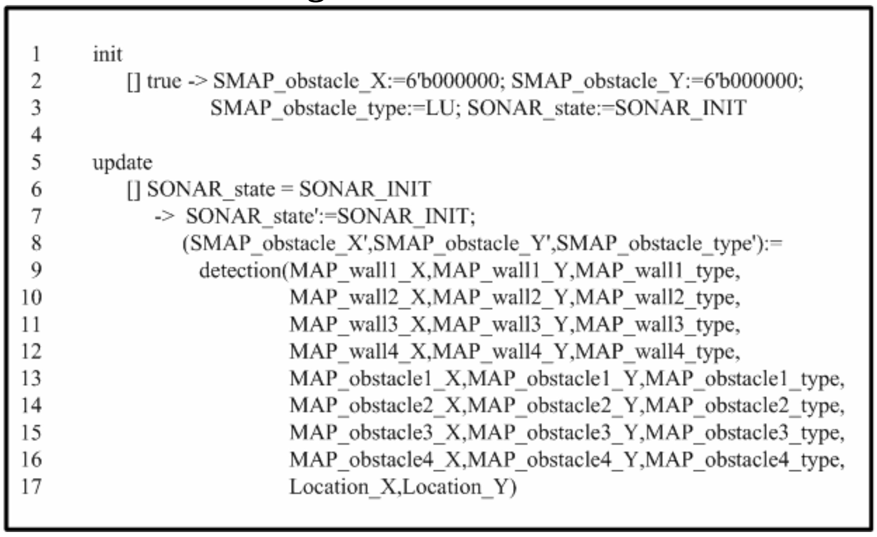
The introduction for all variables in SONAR module is shown in Table 5-3. In each round, SONAR module reads `MAP_obstacle1-4` and `MAP_wall1-4` from MAP, and reads

`Location` and `Location_updated` from MOTOR, and then it updates the updated value of `SMAP_obstacle` and `SONAR_flag`. The interface `SMAP_obstacle` and `SONAR_flag` connect to FORCE_ACCELERATION and RANDOM_ACCELERATION modules for informing the robot centered map of obstacles and walls. The private variable `SONAR_state` is for storing the state of SONAR module.

External	***Receive from***	***Functionality***
`MAP_wall1~4`	MAP	The position of the walls
`MAP_obstacle1~4`	MAP	The position of the obstacles
`Location`	SONAR	Location of the robot
`Location_updated`	SONAR	Inform whether the robot changes its location at last update round.
Interface	***Send to***	***Functionality***
`SMAP_obstacle`	FORCE_ACCELERATION RANDOM_ACCELERATION	Inform the robot centered map of obstacles and walls
`SONAR_flag`	FORCE_ACCELERATION RANDOM_ACCELERATION	Inform whether `SMAP_obstacle` is updated at this update round.
Private		***Functionality***
`SONAR_state`		Store current state of SONAR

Table 5-3 All variables in SONAR module

Comment for UNITY fragment of SONAR



```
init
    [] true -> SMAP_obstacle_X:=6'b000000; SMAP_obstacle_Y:=6'b000000;
               SMAP_obstacle_type:=LU; SONAR_state:=SONAR_INIT

update
    [] SONAR_state = SONAR_INIT
        -> SONAR_state':=SONAR_INIT;
           (SMAP_obstacle_X',SMAP_obstacle_Y',SMAP_obstacle_type'):=
             detection(MAP_wall1_X,MAP_wall1_Y,MAP_wall1_type,
                       MAP_wall2_X,MAP_wall2_Y,MAP_wall2_type,
                       MAP_wall3_X,MAP_wall3_Y,MAP_wall3_type,
                       MAP_wall4_X,MAP_wall4_Y,MAP_wall4_type,
                       MAP_obstacle1_X,MAP_obstacle1_Y,MAP_obstacle1_type,
                       MAP_obstacle2_X,MAP_obstacle2_Y,MAP_obstacle2_type,
                       MAP_obstacle3_X,MAP_obstacle3_Y,MAP_obstacle3_type,
                       MAP_obstacle4_X,MAP_obstacle4_Y,MAP_obstacle4_type,
                       Location_X,Location_Y)
```

Fig. 5-9 UNITY fragment of SONAR： Set initial value for variables of SONAR at initial round, and compute the updated value of `SMAP_obstacle` by external function `detection()` at each update round.

In the UNITY fragment of SONAR shown as Fig. 5-9, we set initial value for variables of SONAR at initial round, and compute the updated value of `SMAP_obstacle` by external function `detection()` at each update round. Because the strategy of computing `SMAP_obstacle` is too complicated to write by UNITY code, we implement the strategy by external function `detection()`.

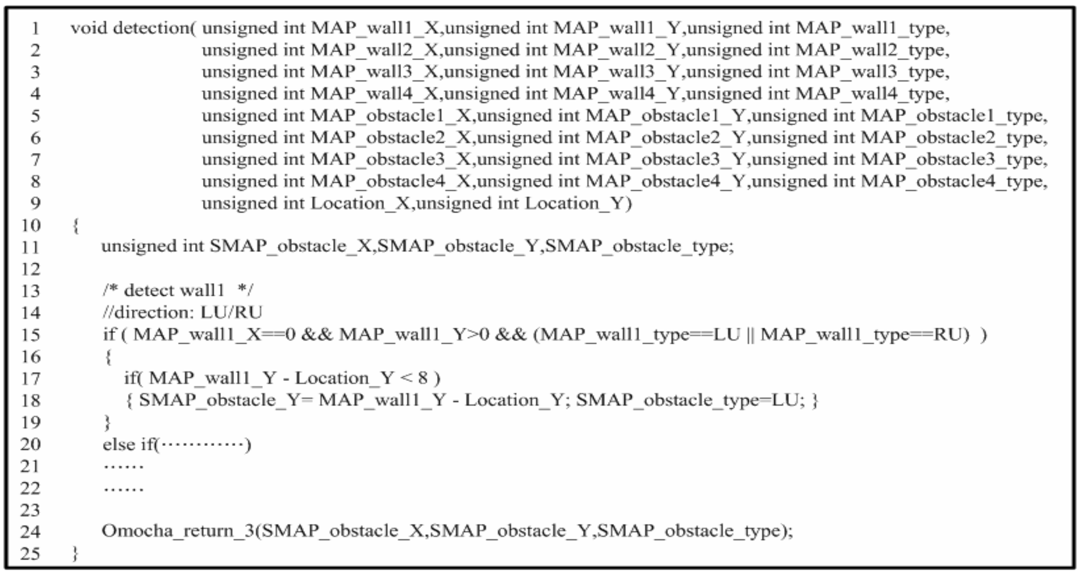
Line 2-3： Set initial value for `SMAP_obstacle`

Line 5： The update action of atoms is specified by the keywords **`update`.**

Line 6： In this update rule, if latched value of `SONAR_state` is SONAR_INIT, Line7-17 will be executed.

Line 7： The updated value of `SONAR_state` is updated to SONAR_INIT

Line 8-17： The updated value of `SMAP_obstacle` is computed by external function `detection()`



```
1   void detection( unsigned int MAP_wall1_X,unsigned int MAP_wall1_Y,unsigned int MAP_wall1_type,
2                   unsigned int MAP_wall2_X,unsigned int MAP_wall2_Y,unsigned int MAP_wall2_type,
3                   unsigned int MAP_wall3_X,unsigned int MAP_wall3_Y,unsigned int MAP_wall3_type,
4                   unsigned int MAP_wall4_X,unsigned int MAP_wall4_Y,unsigned int MAP_wall4_type,
5                   unsigned int MAP_obstacle1_X,unsigned int MAP_obstacle1_Y,unsigned int MAP_obstacle1_type,
6                   unsigned int MAP_obstacle2_X,unsigned int MAP_obstacle2_Y,unsigned int MAP_obstacle2_type,
7                   unsigned int MAP_obstacle3_X,unsigned int MAP_obstacle3_Y,unsigned int MAP_obstacle3_type,
8                   unsigned int MAP_obstacle4_X,unsigned int MAP_obstacle4_Y,unsigned int MAP_obstacle4_type,
9                   unsigned int Location_X,unsigned int Location_Y)
10  {
11      unsigned int SMAP_obstacle_X,SMAP_obstacle_Y,SMAP_obstacle_type;
12
13      /* detect wall1  */
14      //direction: LU/RU
15      if ( MAP_wall1_X==0 && MAP_wall1_Y>0 && (MAP_wall1_type==LU || MAP_wall1_type==RU)  )
16      {
17         if( MAP_wall1_Y - Location_Y < 8 )
18         { SMAP_obstacle_Y= MAP_wall1_Y - Location_Y; SMAP_obstacle_type=LU; }
19      }
20      else if(············)
21      ······
22      ······
23
24      Omocha_return_3(SMAP_obstacle_X,SMAP_obstacle_Y,SMAP_obstacle_type);
25  }
```

Fig. 5-10 Fragment of external function `detection()`

Line 1-9： `detection()` receives `MAP_walls`,`MAP_obstacles` and `Location` as parameters

Line 11： Declare local variable `SMAP_obstacle`.

Line 15-19： Check whether `MAP_wall1` (direction:LU/RU) is in the detection range. If it's true, `SMAP_obstacle_Y` will be set to "`MAP_wall1_Y` - `Location_Y`" and `SMAP_obstacle_type` will be set to "LU".

Line 24： Return the value of local variable `SMAP_obstacle`. The return value will be assigned to interface variable `SMAP_obstacle` in SONAR module.

Example

If (MAP_wall1_X=0, MAP_wall1_Y=8, MAP_wall1_type=LU,

Location_X=18, Location_Y=6)

Then (SMAP_obstacle_X=0, SMAP_obstacle_Y=2, SMAP_obstacle_type=LU)

3. FORCE_ACCELERATION：

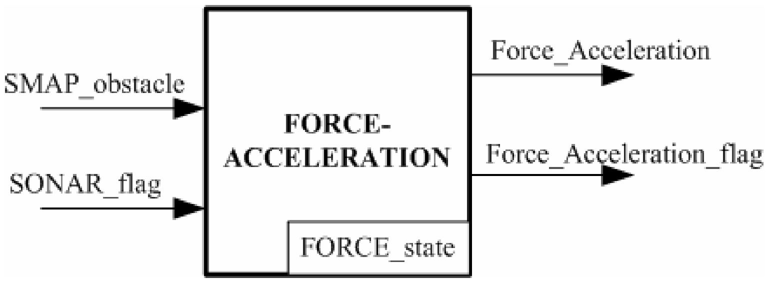


Fig. 5-11 FORCE_ACCELERATION module

As shown in Table 5-1, FORCE_ACCELERATION module has one functionality：

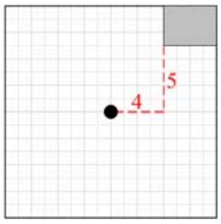
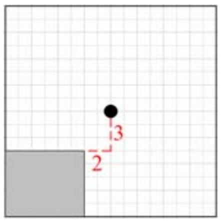
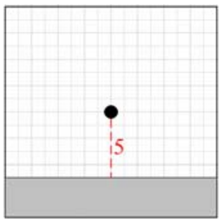
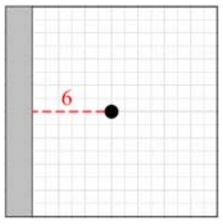
- In each round, FORCE_ACCELERATION awaits robot centered map of obstacles from SONAR module, and compute the Force_Acceleration for RESULT_ACCELERATION module

In FORCE_ACCELERATION module, it receives SMAP_obstacle from SONAR module, and then produces the "reverse acceleration" according to the strategy for avoiding colliding with obstacles, the result of "reverse acceleration" is stored in interface variable Force_Acceleration. The relationship between"distance of X-axis away from the obstacle in SMAP_obstacle" and "X-axis component of reverse acceleration degree in Force_Acceleration" is shown as Table 5-4.

Distance of X-axis away from the obstacle in SMAP_obstacle	0	1	2	3	4	5	6	7
X-axis component of reverse acceleration Degree in Force_Acceleration	0	2	2	2	1	1	1	1

Table 5-4 The relationship between "Distance of X-axis away from the obstacle in SMAP_obstacle" and "X-axis component of reverse acceleration degree in Force_Acceleration". Take X-axis for instance, the situation of Y-axis is equivalent to X-axis

The representation of `Force_Acceleration` is **{ *A-degree* ,*direction* },** the ***A-degree*** is represented by (degree of X-axis component,degree of Y-axis component), and the range of ***A-degree*** is from 0 to 2; the ***direction*** is reverse to the direction of `SMAP_obstacle`. We list some examples to illustrate the relationship between `SMAP_obstacle` and `Force_Acceleration` in Fig. 5-12.

Example				
SMAP_obstacle	**{(4,5),RU}**	**{(2,3),LD}**	**{(0,5),LD/RD}**	**{(6,0),LU/LD}**
Force_Acceleration	**{(1,1),LD}**	**{(2,2),RU}**	**{(0,1),RU/LU}**	**{(1,0),RD/RU}**

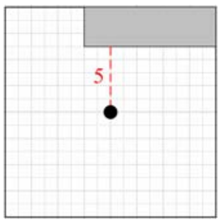
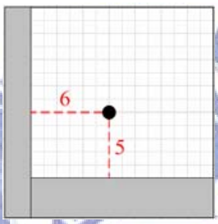
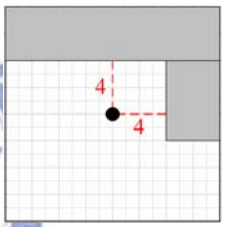
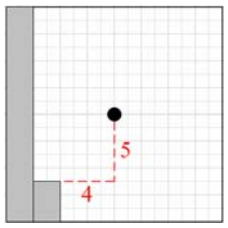
Example				
SMAP_obstacle	**{(0,5),RU}**	**{(6,5),LD}**	**{(4,4),RU}**	**{(4,5),LD}**
Force_Acceleration	**{(0,1),LD}**	**{(1,1),RU}**	**{(1,1),LD}**	**{(1,1),RU}**

Fig. 5-12 Some examples of the relationship between `SMAP_obstacle` and `Force_Acceleration`

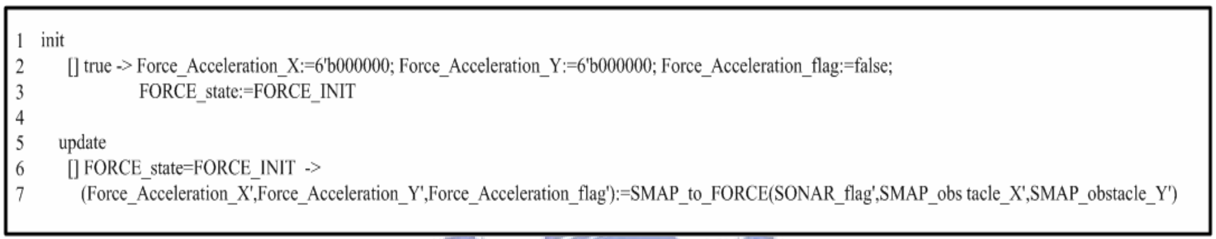
The introduction for all variables in FORCE_ACCELERATION module is shown as Table 5-5. FORCE_ACCELERATION awaits `SMAP_obstacle` from SONAR module, and then updates the updated value of `Force_Acceleration`. The interface `Force_Acceleration` and `Force_Acceleration_flag` connect to RESULT_ACCELERATION module for informing force acceleration.

External	***Receive from***	***Functionality***
`SMAP_obstacle`	SONAR	The robot centered map of obstacles and walls
`SONAR_flag`	SONAR	Inform whether `SMAP_obstacle` is

		updated at this update round
Interface	***Send to***	***Functionality***
`Force_Acceleration`	RESULT_ACCELERATION	Inform the force acceleration for RESULT_ACCELERATION.
`Force_Acceleration_flag`	RESULT_ACCELERATION	Inform whether the updated value of degree of `Force_Acceleration` is non-zero at this update round. It is set true while the updated value of degree of `Force_Acceleration` is not (0,0).
Private		***Functionality***
`FORCE_state`		Store current state of FORCE_ACCELERATION

Table 5-5　All variables in FORCE_ACCLERATION module

Comment for UNITY fragment of FORCE_ACCELERATION



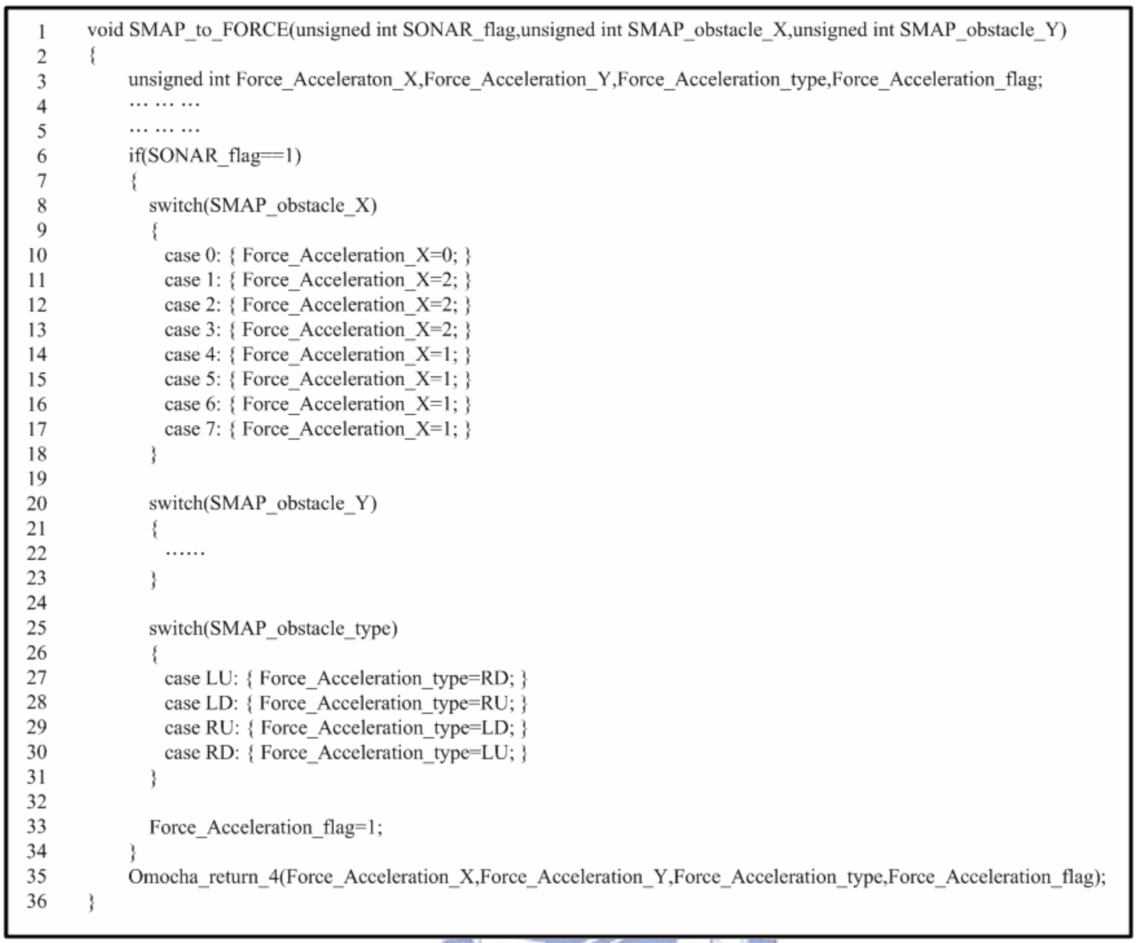
```
1  init
2      [] true -> Force_Acceleration_X:=6'b000000; Force_Acceleration_Y:=6'b000000; Force_Acceleration_flag:=false;
3                  FORCE_state:=FORCE_INIT
4
5    update
6      [] FORCE_state=FORCE_INIT  ->
7        (Force_Acceleration_X',Force_Acceleration_Y',Force_Acceleration_flag'):=SMAP_to_FORCE(SONAR_flag',SMAP_obs tacle_X',SMAP_obstacle_Y')
```

Fig. 5-13　UNITY fragment of FORCE_ACCELERATION：

Set initial value for variables of FORCE_ACCELERATION at initial round, and compute the updated value of `Force_Acceleration` by external function `SMAP_to_FORCE()` at each update round.

Line 2-3：Set initial value for FORCE_ACCELERATION

Line 6-7：The updated value of `Force_Acceleration` is computed by external function `SMAP_to_FORCE()`



```
1    void SMAP_to_FORCE(unsigned int SONAR_flag,unsigned int SMAP_obstacle_X,unsigned int SMAP_obstacle_Y)
2    {
3         unsigned int Force_Acceleraton_X,Force_Acceleration_Y,Force_Acceleration_type,Force_Acceleration_flag;
4         … … …
5         … … …
6         if(SONAR_flag==1)
7         {
8           switch(SMAP_obstacle_X)
9           {
10            case 0: { Force_Acceleration_X=0; }
11            case 1: { Force_Acceleration_X=2; }
12            case 2: { Force_Acceleration_X=2; }
13            case 3: { Force_Acceleration_X=2; }
14            case 4: { Force_Acceleration_X=1; }
15            case 5: { Force_Acceleration_X=1; }
16            case 6: { Force_Acceleration_X=1; }
17            case 7: { Force_Acceleration_X=1; }
18          }
19
20          switch(SMAP_obstacle_Y)
21          {
22            ……
23          }
24
25          switch(SMAP_obstacle_type)
26          {
27            case LU: { Force_Acceleration_type=RD; }
28            case LD: { Force_Acceleration_type=RU; }
29            case RU: { Force_Acceleration_type=LD; }
30            case RD: { Force_Acceleration_type=LU; }
31          }
32
33          Force_Acceleration_flag=1;
34        }
35        Omocha_return_4(Force_Acceleration_X,Force_Acceleration_Y,Force_Acceleration_type,Force_Acceleration_flag);
36   }
```

Fig. 5-14 Fragment of external function `SMAP_to_FORCE()`

Line 1： `SMAP_to_FORCE()` receives `SONAR_flag` and `SMAP_obstacle` as parameters

Line 3： Declare local variable `Force_Acceleration.`

Line 8-18： If `SONAR_flag` is true, we set the value of `Force_Acceleration_X` according to relationship shown in Table 5-4.

Line 25-31： If `SONAR_flag` is true, we set the value of `Force_Acceleration_type` according to relationship shown in Fig. 5-12.

Line 35：Return the value of local variable `Force_Acceleration`. The return value will be assigned to interface variable `Force_Acceleration` in FORCE_ACCELERATION module.

4. RANDOM_ACCELERATION：

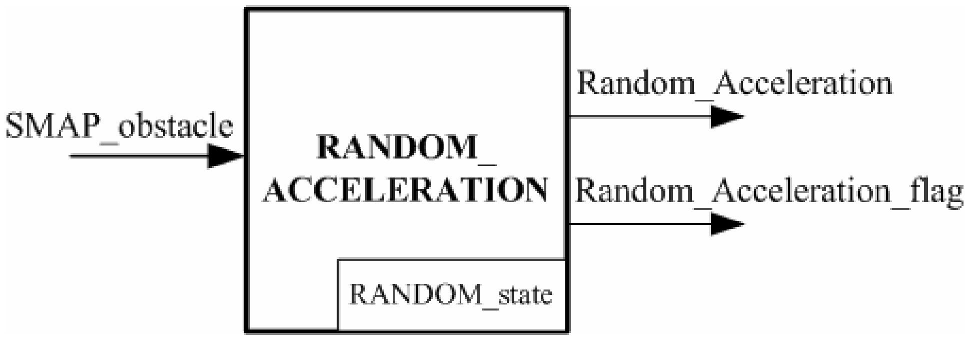


Fig. 5-15 RANDOM_ACCELERATION module

As shown in Table 5-1, RANDOM_ACCELERATION module has one functionality:

- In each round, if there is no any obstacle in detection range (the updated value of `SMAP_obstacle` is { (0,0) , LU)), RANDOM_ACCELERATION module produces a random `Random_Acceleration` for RESULT_ACCELERATION module.

In RANDOM_ACCELERATION module, it awaits `SMAP_obstacle` from SONAR module. If there is no obstacle in detection range (the updated value of `SMAP_obstacle` is {(0,0) , LU}), RANDOM_ACCELERATION module will produce a random acceleration for the robot. The robot can wander aimlessly by changing its velocity according to the random acceleration. The random acceleration which produced by RANDOM_ACCELERATION is stored in interface variable `Random_Acceleration`, and then `Random_Acceleration` will be sent to RESULT_ACCELERATION module.

The representation of `Random_Acceleration` is ***{A-degree ,direction },*** the ***A-degree*** is represented by (degree of X-axis component, degree of Y-axis component), and the range of ***A-degree*** is from 0 to 2; the ***direction*** is one of { LU,LD,RU,RD }. We list some examples of the relationship between `SMAP_obstacle` and `Random_Acceleration` in Fig. 5-16.

The introduction for all variables in RANDOM_ACCELERATION module is shown in

Table 5-6. In each round, RANDOM_ACCELERATION awaits `SMAP_obstacle` from SONAR module, and updates the updated value of `Random_Acceleration` and `Random_Acceleration_flag`. The interface `Random_Acceleration` and `Random_Acceleration_flag` connect to RESULT_ACCELERATION modules for informing the random acceleration.

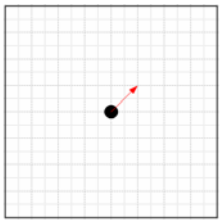
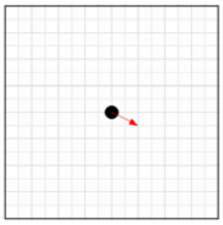
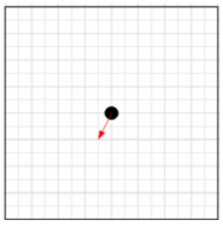
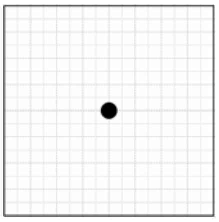
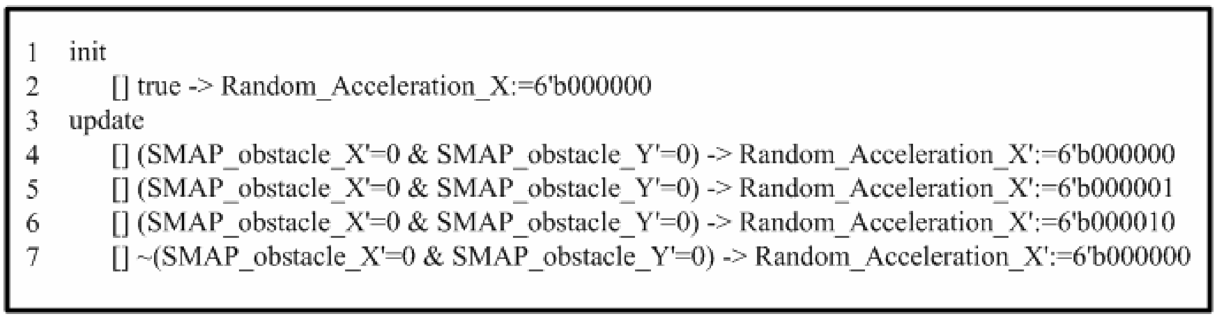
Example				
SMAP_obstacle	**{(0,0),LU}**	**{(0,0),LU}**	**{(0,0),LU}**	**Not {(0,0),LU}**
Random_Acceleration	**{(2,2),RU}**	**{(2,1),RD}**	**{(1,2),LD}**	**{(0,0),LU}**

Fig. 5-16 Some examples of the relationship between `SMAP_obstacle` and `Random_Acceleration`

External	***Receive from***	***Functionality***
`SMAP_obstacle`	SONAR	The robot centered map of obstacles and walls
`SMAP_obstacle_flag`	SONAR	Inform whether `SMAP_obstacle` is updated at this update round
Interface	***Send to***	***Functionality***
`Random_Acceleration`	RESULT_ACCELERATION	Inform the random acceleration for RESULT_ACCELERATION
`Random_Acceleration_flag`	RESULT_ACCELERATION	Inform whether the updated value of degree of `Random_Acceleration` is non-zero at this update round. It is set true while the updated value of the degree of `Random_Acceleration` is not (0,0).
Private		***Functionality***
`RANDOM_state`		Store current state of RANDOM_ACCELERATION

Table 5-6. All variables in RANDOM_ACCLERATION module

Comment for UNITY fragment of RANDOM_ACCELERATION



```
1  init
2      [] true -> Random_Acceleration_X:=6'b000000
3  update
4      [] (SMAP_obstacle_X'=0 & SMAP_obstacle_Y'=0) -> Random_Acceleration_X':=6'b000000
5      [] (SMAP_obstacle_X'=0 & SMAP_obstacle_Y'=0) -> Random_Acceleration_X':=6'b000001
6      [] (SMAP_obstacle_X'=0 & SMAP_obstacle_Y'=0) -> Random_Acceleration_X':=6'b000010
7      [] ~(SMAP_obstacle_X'=0 & SMAP_obstacle_Y'=0) -> Random_Acceleration_X':=6'b000000
```

Fig. 5-17 UNITY fragment of RANDOM_ACCELERATION：
Set the initial value for variables of RANDOM_ACCELERATION at initial round, and update the updated value of `Random_Acceleration_X` at each update round.

Line 2： Set initial value for RANDOM_ACCELERATION

Line 4-6：If (`SMAP_obstacle_X,SMAP_obstacle_Y`) is (0,0), the value of `Random_Acceleration_X` will randomly be set to one of {0,1,2}

Line 7：If one of `SMAP_obstacle_X` and `SMAP_obstacle_Y` is not 0, the value of `Random_Acceleration_X` will be set to 0.

5. RESULT_ACCELERATION：

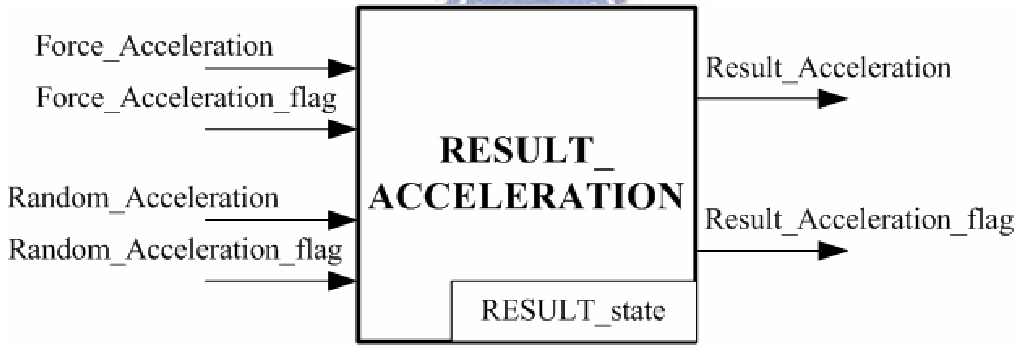


Fig. 5-18 RESULT_ACCELERATION module

As shown in Table 5-1, RESULT_ACCELERATION module has one functionality：

- In each round, RESULT_ACCELERATION awaits `Force_Acceleration` and `Random_Acceleration`, and then determine which one to output as `Result_Acceleration` for VELOCITY module

In RESULT_ACCELERATION module, it awaits `Force_Acceleration` and

Random_Acceleration, and then determines which one to output as Result_Accleration for VELOCITY module. The strategy for making the decision is listed below:

A. Force_Acceleration_flag==true&&Random_Acceleration_flag==false/ true→ Result_Acceleration = Force_Acceleration

B. Force_Acceleration_flag==false&&Random_Acceleration_flag==true → Result_Acceleration = Random_Acceleration

C. Force_Acceleration_flag==false&&Random_Acceleration_flag==false →Result_Acceleration = { (0,0) , LU }

The strategy includes three conditions：

A. If Force_Acceleration_flag is true, Force_Acceleration will be stored in Result_Acceleration.

B. If Force_Acceleration_flag is false and Random_Acceleration_flag is true, Random_Acceleration will be stored in Result_Acceleration.

C. If Force_Acceleration_flag and Random_Acceleration_flag are both false, Result_Acceleration will be set to { (0,0) , LU }.

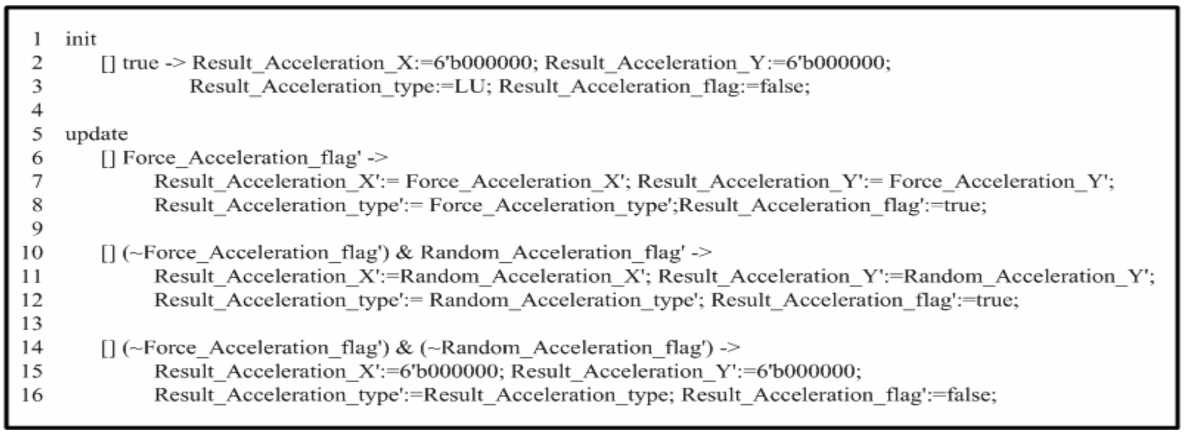
The strategy will make the robot avoid collision while there are some obstacles in detection range ,and wander aimlessly while there is no obstacle in detection range.

The introduction for all variables in RESULT_ACCELERATION module is shown in Table 5-7. RESULT_ACCELERATION awaits Force_Acceleration from FORCE_-ACCELERATION and Random_Acceleration from RANDOM_ACCELERATION, and then updates the updated value of Result_Acceleration. The interface Result_Acceleration and Result_Acceleration_flag connect to VELOCITY module for informing result acceleration.

External	***Receive from***	***Functionality***
`Force_Acceleration`	FORCE_ACCELERATION	Inform the acceleration produced by FORCE_ACCELERATION
`Force_Acceleration_flag`	FORCE_ACCELERATION	Inform whether the updated value of degree of `Force_Acceleration` is non-zero at this update round
`Random_Acceleration`	RANDOM_ACCELERATION	Inform the random acceleration produced by RANDOM_ACCELERATION
`Random_Acceleration_flag`	RANDOM_ACCELERATION	Inform whether the updated value of degree of `Random_Acceleration` is non-zero at this update round
Interface	***Send to***	***Functionality***
`Result_Acceleration`	VELOCITY	Inform the result acceleration for VELOCITY
`Result_Acceleration_flag`	VELOCITY	Inform whether the updated value of degree of `Result_Acceleration` is non-zero at this update round. It is set true while the updated value of degree of `Result_Acceleration` is not (0,0).
Private		***Functionality***
`RESULT_state`		Store current state of RESULT_ACCELERATION

Table 5-7. All variables in RESULT_ACCLERATION module

Comment for UNITY fragment of RESULT_ACCELERATION



```
init
    [] true -> Result_Acceleration_X:=6'b000000; Result_Acceleration_Y:=6'b000000;
               Result_Acceleration_type:=LU; Result_Acceleration_flag:=false;

update
    [] Force_Acceleration_flag' ->
          Result_Acceleration_X':= Force_Acceleration_X'; Result_Acceleration_Y':= Force_Acceleration_Y';
          Result_Acceleration_type':= Force_Acceleration_type';Result_Acceleration_flag':=true;

    [] (~Force_Acceleration_flag') & Random_Acceleration_flag' ->
          Result_Acceleration_X':=Random_Acceleration_X'; Result_Acceleration_Y':=Random_Acceleration_Y';
          Result_Acceleration_type':= Random_Acceleration_type'; Result_Acceleration_flag':=true;

    [] (~Force_Acceleration_flag') & (~Random_Acceleration_flag') ->
          Result_Acceleration_X':=6'b000000; Result_Acceleration_Y':=6'b000000;
          Result_Acceleration_type':=Result_Acceleration_type; Result_Acceleration_flag':=false;
```

Fig. 5-19 UNITY fragment of RESULT_ACCELERATION：

First, set initial value for variables of RESULT_ACCELERATION at initial round, and determine the updated value of `Result_Acceleration` at each update round.

Line 2-3： Set initial value for RESULT_ACCELERATION

Line 6-8：If the updated value of `Force_Acceleration_flag` is true, the updated value of `Force_Acceleration` will be stored in the updated value of `Result_Acceleration`, and the updated value of `Result_-Acceleration_flag` will be set to true.

Line 10-12：If the updated value of `Force_Acceleration_flag` is false and the updated value of `Random_Acceleration_flag` is true, the updated value of `Random_Acceleration` will be stored in the updated value of `Result_Acceleration`, and the updated value of `Result_Acceleration` will be set to true.

Line 14-16：If the updated value of `Force_Acceleration_flag` and the updated value of `Random_Acceleration_flag` are both false, the updated value of `Result_Acceleration` will be set to (0,0,LU), and the updated value of `Result_Acceleration_flag` will be set to false.

6. VELOCITY：

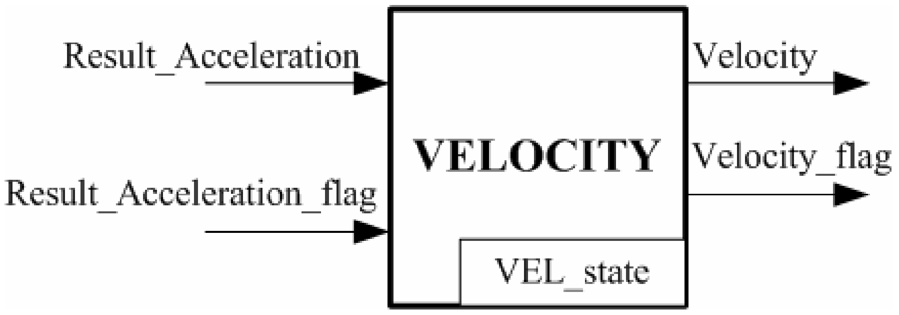


Fig. 5-20 VELOCITY module

As shown in Table 4-1, VELOCITY module has one functionality：

- In each round, VELOCITY awaits `Result_Acceleration` from RESULT_ACCELERATION module, and then updates `Velocity.`

In VELOCITY module, the interface variable `Velocity` stores the velocity of the robot.

Once receiving `Result_Acceleration` from RESULT_ACCELERATION, VELOCITY module will update `Velocity` by combining with `Result_Acceleration`. The representation of `Velocity` is **{ *V-degree* ,*direction* },** the ***V-degree*** is represented by (degree of X-axis component, degree of Y-axis component), and the range of ***V-degree*** is from 0 to 2; the ***direction*** is one of { LU, LD,RU,RD }. We list some examples of updating `Velocity` in Fig. 5-21. After updating `Velocity`, `Velocity` will be sent to MOTOR module for updating robot's location.

The introduction for all variables in VELOCITY module is shown in Table 5-8. VELOCITY awaits `Result_Acceleration` from RESULT_ACCELERATION, and then updates the updated value of `Velocity`. The interface `Velocity` connects to MOTOR module for informing robot's velocity.

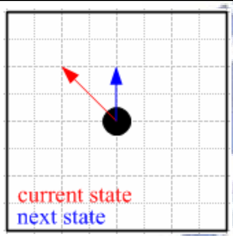
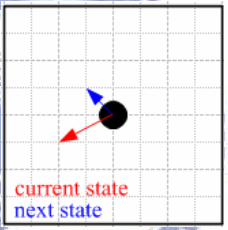
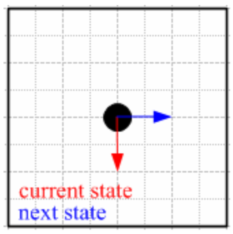
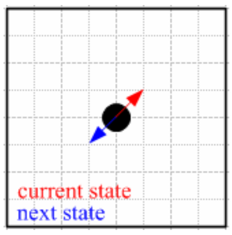
Example				
`Result_Acceleration`	**{(2,0),RU/RD}**	**{(1,2),RU}**	**{(2,2),RU}**	**{(2,2),LD}**
`Velocity` before updating (current state)	**{(2,2),LU}**	**{(2,1),LD}**	**{(0,2),LD/RD}**	**{(1,1),RU}**
`Velocity` after updating (next state)	**{(0,2),LU/RU}**	**{(1,1),LU}**	**{(2,0),RU/RD}**	**{(1,1),LD}**

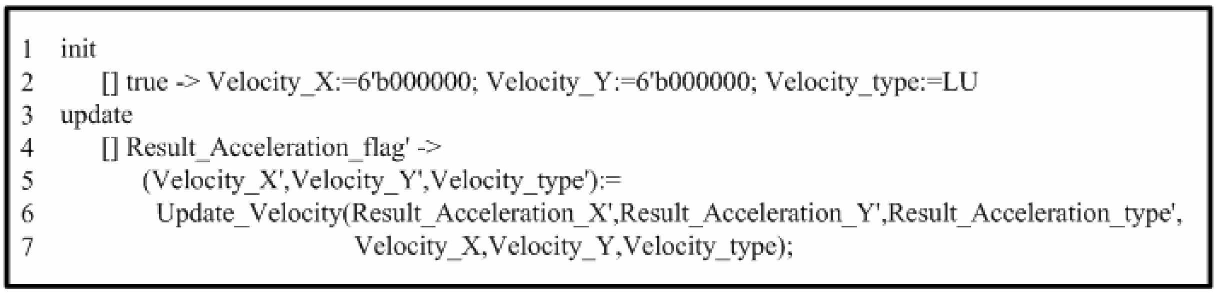
Fig. 5-21 Some examples of updating `Velocity`

External	***Receive from***	***Functionality***
`Result_Acceleration`	RESULT_ACCELERATION	Inform the acceleration determined by RESULT_ACCELERATION
`Result_Acceleration_flag`	RESULT_ACCELERATION	Inform whether the updated value of degree of `Result_Acceleration` is non-zero at this update round
Interface	***Send to***	***Functionality***
`Velocity`	MOTOR	Inform the velocity for MOTOR

Private		*Functionality*
`VELOCITY_state`		Store current state of VELOCITY

Table 5-8. All variables in VELOCITY module

Comment for UNITY fragment of VELOCITY



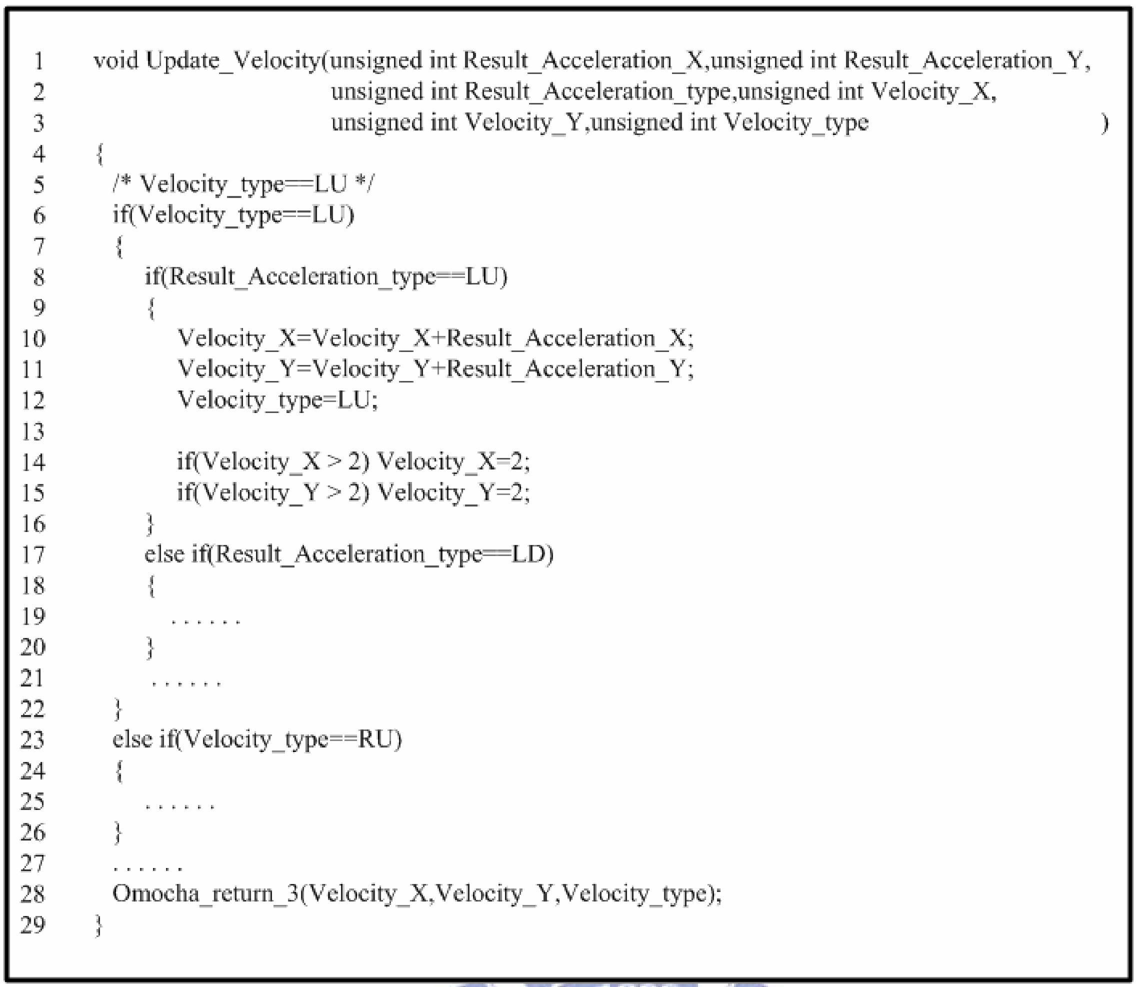
```
1  init
2      [] true -> Velocity_X:=6'b000000; Velocity_Y:=6'b000000; Velocity_type:=LU
3  update
4      [] Result_Acceleration_flag' ->
5          (Velocity_X',Velocity_Y',Velocity_type'):=
6            Update_Velocity(Result_Acceleration_X',Result_Acceleration_Y',Result_Acceleration_type',
7                                   Velocity_X,Velocity_Y,Velocity_type);
```

Fig. 5-22 UNITY fragment of VELOCITY：

First, set initial value for variables of VELOCITY. The updated value of `Velocity` is computed by external function `Update_Velocity()`

Line 2：Set initial value for VELOCITY

Line 4-7：The updated value of `Velocity` is computed by external function `Update_Velocity()`



```
1     void Update_Velocity(unsigned int Result_Acceleration_X,unsigned int Result_Acceleration_Y,
2                          unsigned int Result_Acceleration_type,unsigned int Velocity_X,
3                          unsigned int Velocity_Y,unsigned int Velocity_type                    )
4     {
5       /* Velocity_type==LU */
6       if(Velocity_type==LU)
7       {
8          if(Result_Acceleration_type==LU)
9          {
10            Velocity_X=Velocity_X+Result_Acceleration_X;
11            Velocity_Y=Velocity_Y+Result_Acceleration_Y;
12            Velocity_type=LU;
13
14            if(Velocity_X > 2) Velocity_X=2;
15            if(Velocity_Y > 2) Velocity_Y=2;
16         }
17         else if(Result_Acceleration_type==LD)
18         {
19            . . . . . .
20         }
21          . . . . . .
22      }
23      else if(Velocity_type==RU)
24      {
25         . . . . . .
26      }
27      . . . . . .
28      Omocha_return_3(Velocity_X,Velocity_Y,Velocity_type);
29    }
```

Fig. 5-23 Fragment of external function `Update_Velocity()`

Line 1-3： `Update_Velocity()` receives `Result_Acceleration` and `Velocity` as parameters

Line 6-12： If `Velocity_type` and `Result_Acceleration_type` are both LU, we update `Velocity` by combining with `Result_Acceleration`, and `Velocity_type` will still be LU.

Line 14-15：Because the range of ***V-degree*** is from 0 to 2, If the degree of `Velocity` is larger than 2 after combination with `Result_Acceleration`,the degree of `Velocity` will be set to 2

Line 28：Return the value of local variable `Velocity`. The return value will be assigned to interface variable `Velocity` in VELOCITY module.

7. MOTOR：

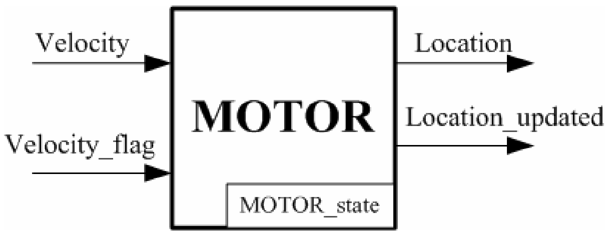


Fig. 5-24　MOTOR module

As shown in Table 5-1,MOTOR module has two functionalities：

- In each round, MOTOR awaits `Velocity` from VELOCITY, and then update `Location`.
- Set `Location_updated` flag to true while updated value of `Location` isn't equal to latched value of `Location`

In MOTOR module, the interface variable `Location` stores the location of the robot, the initial value of `Location` represents the initial location of the robot. `Location_updated` will be set to true while `Location` is updated. Once receiving `Velocity` from VELOCITY, MOTOR module will update `Location` according to `Velocity`, and `Location_updated` will be set to true. We list some examples of updating `Location` in Fig. 5-25.

The introduction for all variables in MOTOR module is shown in Table 5-9. MOTOR awaits `Velocity` from VELOCITY, and then updates the updated value of `Location`. The interface `Location` connects to SONAR module for informing robot's location.

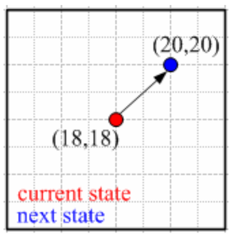
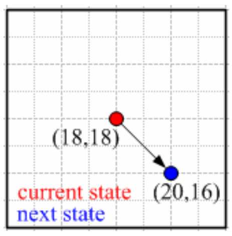
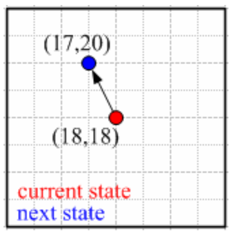
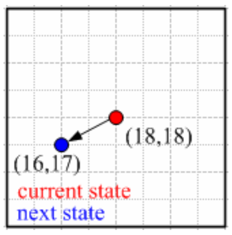
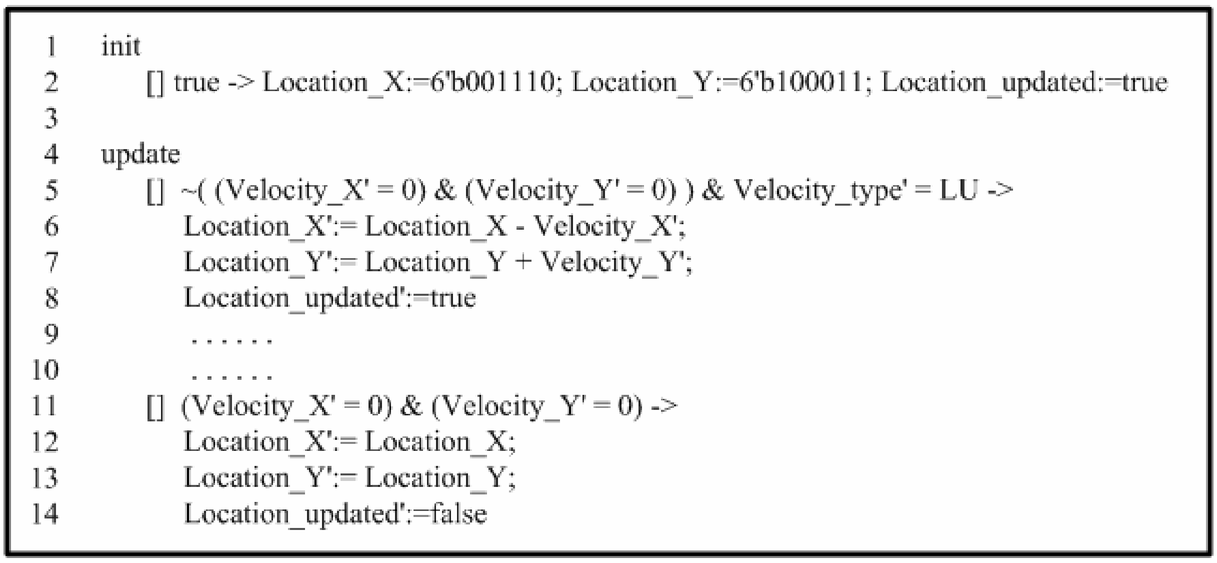
Example				
`Velocity`	**{(2,2),RU}**	**{(2,2),RD}**	**{(1,2),LU}**	**{(2,1),LD}**
`Location` before updating	**(18,18)**	**(18,18)**	**(18,18)**	**(18,18)**
`Location` after updating	**(20,20)**	**(20,16)**	**(17,20)**	**(16,17)**

Fig. 5-25 Some examples of updating `Location`

External	***Receive from***	***Functionality***
`Velocity`	VELOCITY	Inform the updated value of `Velocity` at this update round.
Interface	***Send to***	***Functionality***
`Location`	SONAR	Inform the location of robot for SONAR
`Location_updated`	SONAR	Inform whether the updated value of `Location` is updated at this update round
Private		***Functionality***
`MOTOR_state`		Store current state of MOTOR

Table 5-9. All variables in MOTOR module

Comment for UNITY fragment of MOTOR



```
1   init
2       [] true -> Location_X:=6'b001110; Location_Y:=6'b100011; Location_updated:=true
3
4   update
5       [] ~( (Velocity_X' = 0) & (Velocity_Y' = 0) ) & Velocity_type' = LU ->
6           Location_X':= Location_X - Velocity_X';
7           Location_Y':= Location_Y + Velocity_Y';
8           Location_updated':=true
9           ......
10          ......
11      [] (Velocity_X' = 0) & (Velocity_Y' = 0) ->
12          Location_X':= Location_X;
13          Location_Y':= Location_Y;
14          Location_updated':=false
```

Fig. 5-26 UNITY fragment of MOTOR：
First, set initial value for variables of MOTOR at initial round, and update the updated value of `Location` and `Location_updated` at each update round.

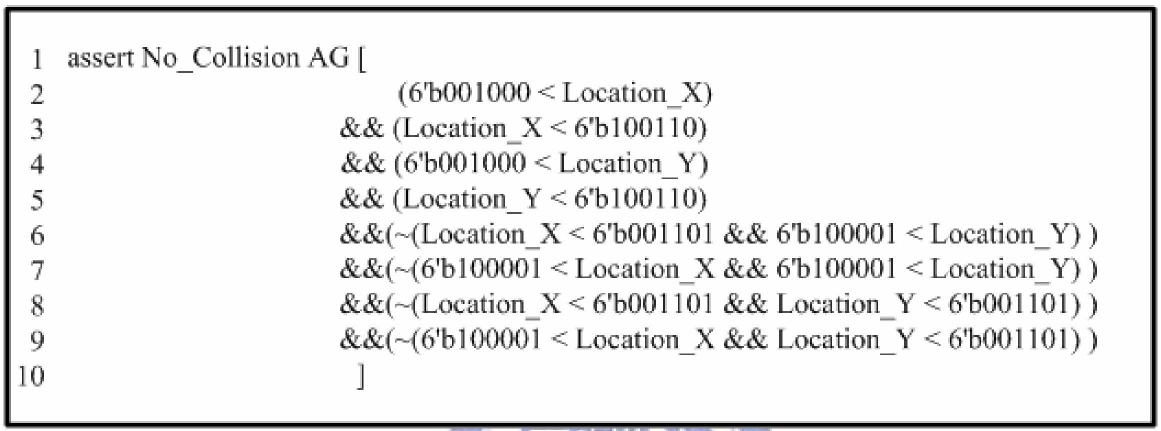
Line 1-2：Set initial value for MOTOR

Line 5-8： If the updated value of `Velocity` isn't (0,0), we update the updated value of `Location` according to `Velocity`.

Line 11-14： If the updated value of `Veloctiy` is (0,0), we remain the latched value of `Location`, and set the updated value of `Location_updated` to false.

5.3 Property To Be Verified：“No_Collision” Property

The *“No_Collision”* property is shown as Fig. 5-27. We had discussed how to describe properties with Temporal Logic in Section 3.3.1, the two parts of Temporal Logic are “The propositional logic formula” and “The temporal connectives”, the two parts of “No_Collision” are listed in Table 5-10. If the behaviors of robot satisfy the “No_Collision” property, it means the robot won’t collide with walls or obstacles in the environment.



```
1  assert No_Collision AG [
2                              (6'b001000 < Location_X)
3                          && (Location_X < 6'b100110)
4                          && (6'b001000 < Location_Y)
5                          && (Location_Y < 6'b100110)
6                          &&(~(Location_X < 6'b001101 && 6'b100001 < Location_Y) )
7                          &&(~(6'b100001 < Location_X && 6'b100001 < Location_Y) )
8                          &&(~(Location_X < 6'b001101 && Location_Y < 6'b001101) )
9                          &&(~(6'b100001 < Location_X && Location_Y < 6'b001101) )
10                           ]
```

Fig. 5-27 “No_Collision” property checked by OMocha

Line 1： The temporal connectives of “No_Collision” property is “AG”, it means that all reachable states will satisfy the propositional logic formula.

Line 2-5： Check whether the robot will collide with walls.

Line 6-9： Check whether the robot will collide with obstacles.

The propositional logic formula	(6'b001000 < Location_X) && (Location_X < 6'b100110) && (6'b001000 < Location_Y) && (Location_Y < 6'b100110) &&(~(Location_X < 6'b001101 && 6'b100001 < Location_Y)) &&(~(6'b100001 < Location_X && 6'b100001 < Location_Y)) &&(~(Location_X < 6'b001101 && Location_Y < 6'b001101)) &&(~(6'b100001 < Location_X && Location_Y < 6'b001101))
The temporal connectives	AG

Table 5-10 “No_Collision” property

Chapter 6

Experiment Results and Analysis

In Section 6.1, we will explain the three approaches applied to the experiment, they include (A) *state hiding*, (B) Coarse Sampling of States, and (C) *elimination of some checking cases*. In Section 6.3, we will check the "No_Collision" property by OMocha, and show the checking results of some different cases. In Section 6.4, we will analysis the checking results.

6.1 State Hiding Applied to the Experiment

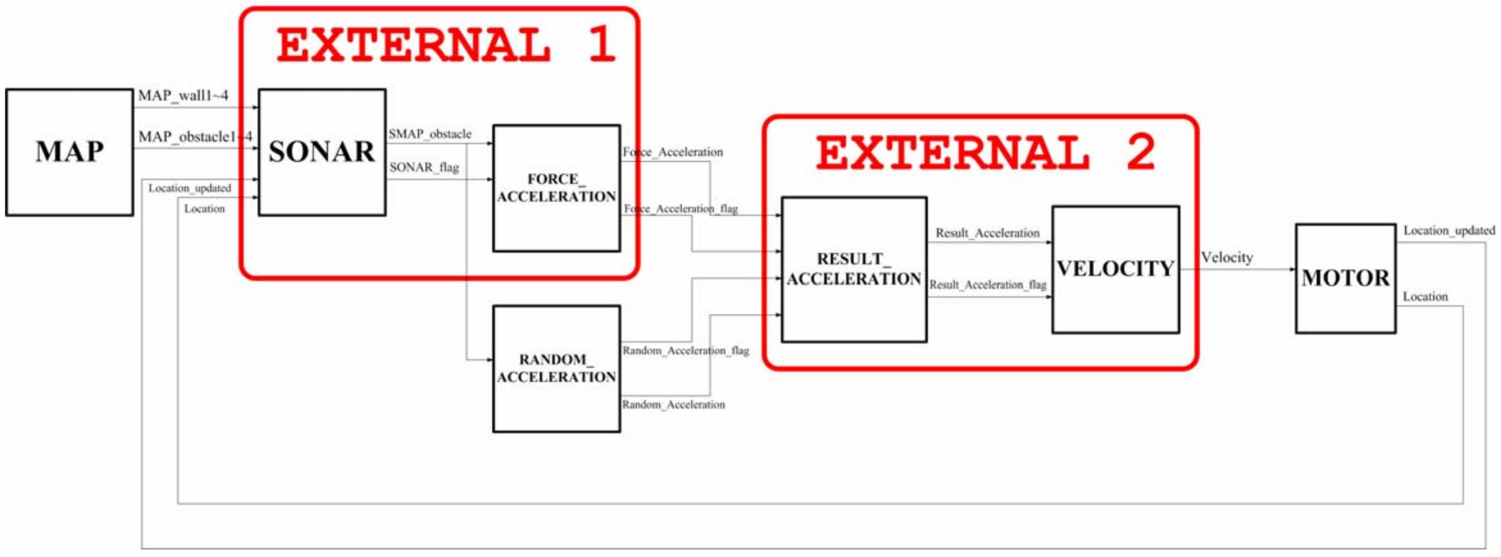


Fig. 6-1 Some variables encapsulated into external function

According to encapsulation principle and the experiment characteristics, we can combine SONAR and FORCE_ACCELERATION modules into EXTERNAL1 module, and combine RESULT_ACCELERATION and VELOCITY modules into EXTERNAL2 module. The After encapsulation procedure, the full structure of the experiment is shown as Fig. 6-1.

After encapsulation, some variables are moved out from UNITY-based programs, these variables include `SMAP_obstacle`, `SONAR_flag`, `Result_Acceleration` and `Result_Acceleration_flag`.

6.2 Elimination of Some Checking Cases Applied to the Experiment

6.2.1 Principle

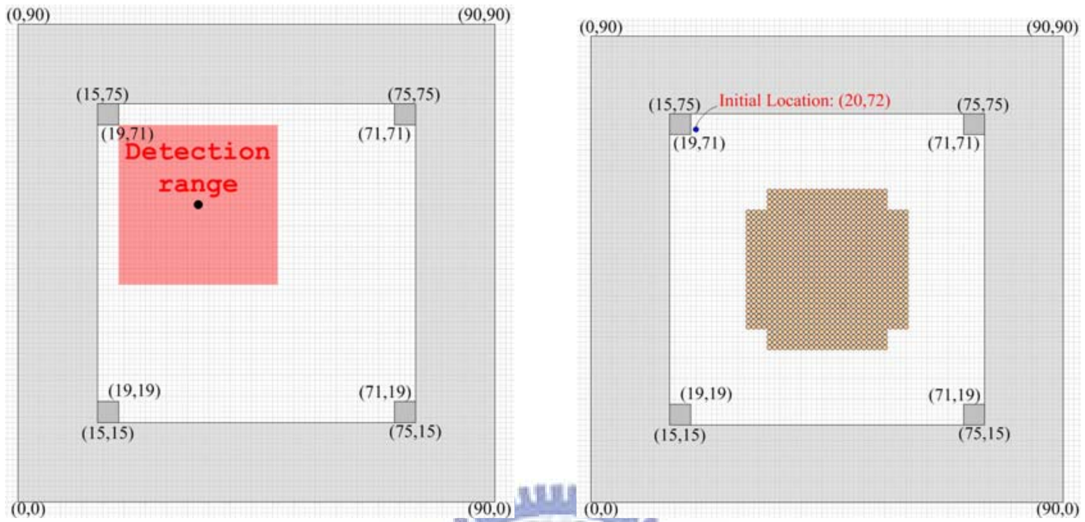


Fig. 6-2 Wandering Region

(a) A point where there is no obstacle in detection range.

(b) The full set of points where there is no obstacle in detection range is called “wandering region”

In Fig. 6-2, we show a point where there is no obstacle in detection range in (a), and show the full set of points where there is no obstacle in detection range in (b). We call the range of the full set of points *“wandering region”*. When the location of the robot is in wandering region, there are some non-deterministic choices during update round. For example, when the robot is in wandering region and its location is (34,56), there is no obstacle in its detection range, so `Random_Acceleration` produced randomly will be stored into `Result_Acceleration`, the number of all possible combination of `Random_Acceleration` is 72[1]; Therefore, the number of next states for the state(`Location` is (34,56)) is 72.

We can observe that the number of all reachable states greatly grow up while the robot moves into wandering region. In order to reduce the number of all reachable states we present an approach to eliminate parts of checking cases, the approach will be explained in detail below.

[1] `Random_Acceleration_X` is one of {0,1,2}, `Random_Acceleartion_Y` is one of {0,1,2}, `Random_Acceleration_type` is one of {LU,LD,RU,RD}, `Random_Acceleration_flag` is one of {true , false}, therefore the number of all possible combination is 3*3*4*2=72

6.2.2 Approach for Smart Elimination

We can assume that when the robot wanders aimlessly in wandering region it will never collide with obstacles. Therefore, if we can eliminate parts of checking cases during wandering in wandering region, we will greatly reduce the number of all reachable states. An example for full verification procedure is shown as Fig. 6-3. According to above-mentioned assumption, we know the parts of full verification procedure between states in wandering region can be eliminated. In Fig. 6-4, the parts of full verification procedure between states in wandering region are marked with dotted circle, and the left parts of full verification procedure which still need to be checked are marked with solid circle. The parts of full verification procedure marked with solid circle are approximately equivalent to another partial verification procedure shown as Fig. 6-5.

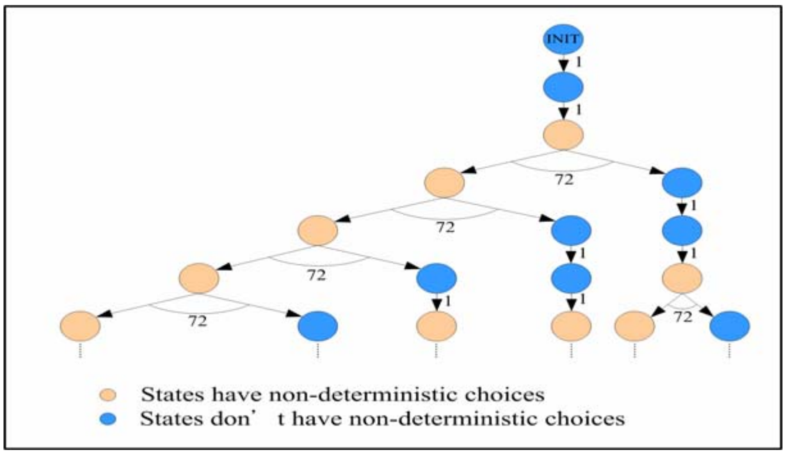

INIT
1
1
72
72
72
72
72
1
1
1
1
1
States have non-deterministic choices
States don' t have non-deterministic choices

Fig. 6-3 An example for full verification procedure

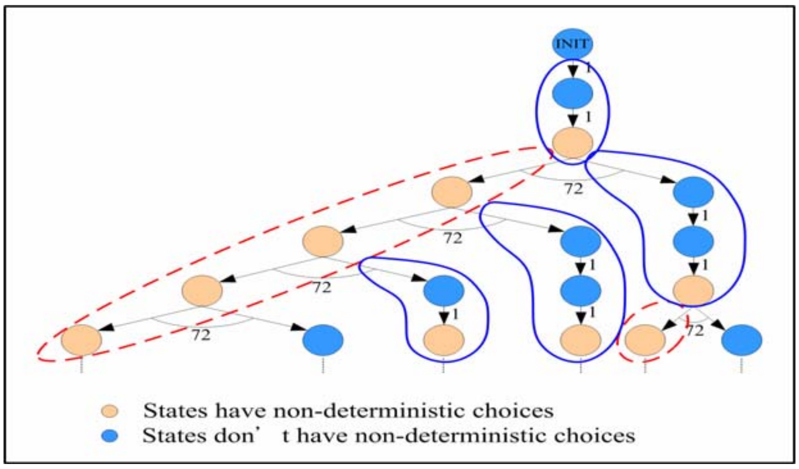

INIT
1
1
72
72
72
72
72
1
1
1
1
1
States have non-deterministic choices
States don' t have non-deterministic choices

Fig. 6-4 The parts of full verification procedure marked with dotted circle can be eliminated, and the left parts of verification procedure marked with solid circle still need to be c checked.

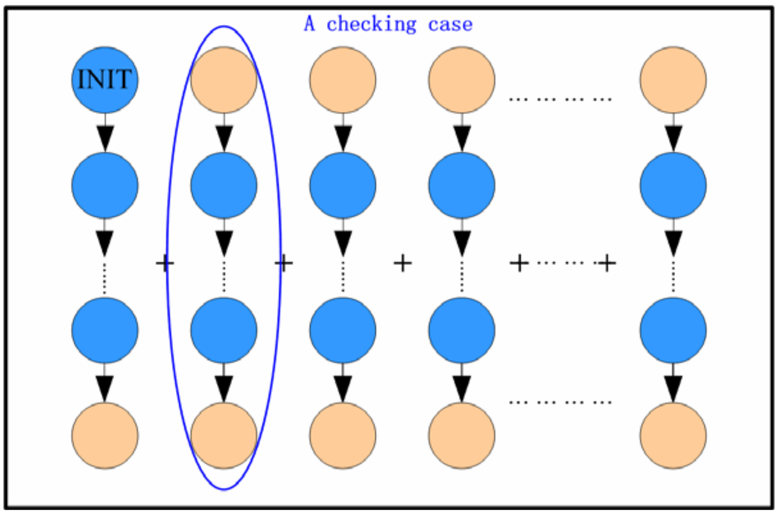


Fig. 6-5 The partial verification procedure is the collection of checking cases.

The partial verification procedure is the collection of checking cases. Each checking case begins from a state in wandering region, and then traces through some states which have no obstacle in detection range, and terminates when reaching a state in wandering region again.

All beginning states of these checking cases include : (1)Initial state and (2) parts of states in wandering region, which can make the location of next state is not in wandering region. The all possible velocities of a state in wandering region which can make the location of next state is not in wandering region is shown as Fig. 6-6. Three examples of checking cases are shown as Fig. 6-7.

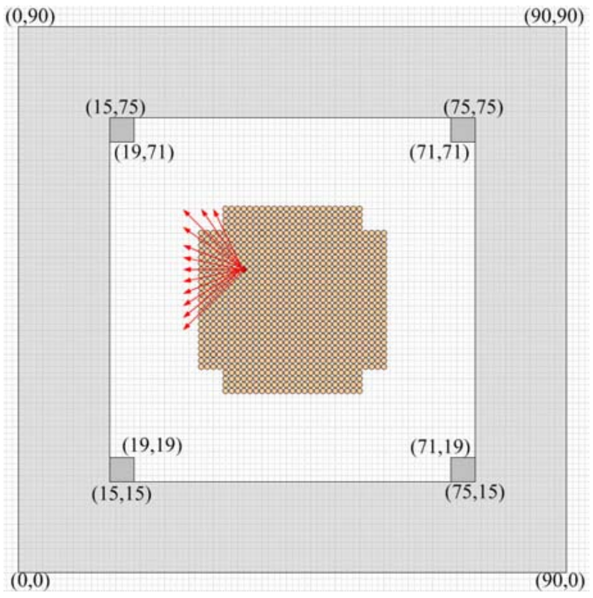


Fig. 6-6 Outward velocities make the robot leave the wandering region

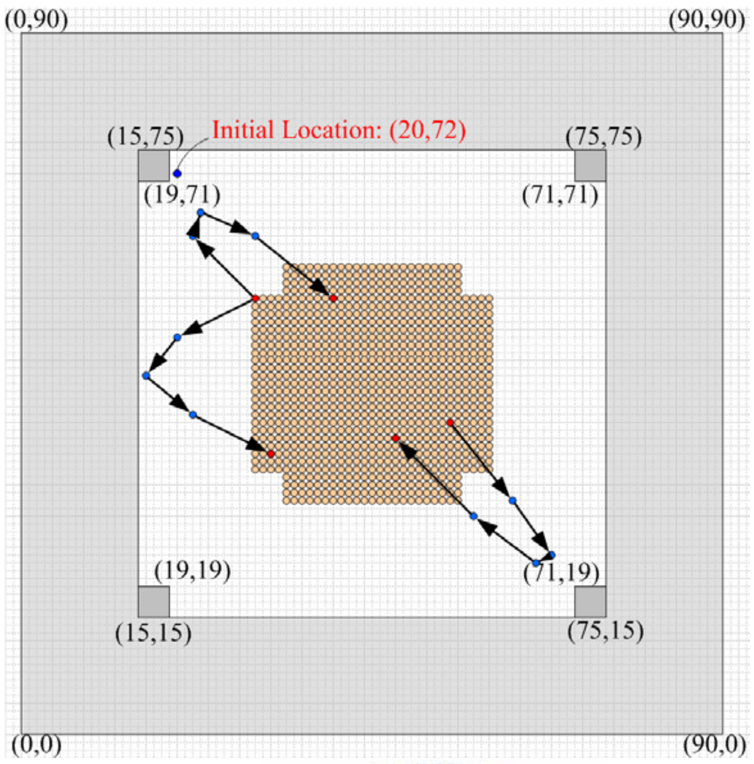


Fig. 6-7 Three examples of checking cases

6.2.3 Approach for Partial Elimination

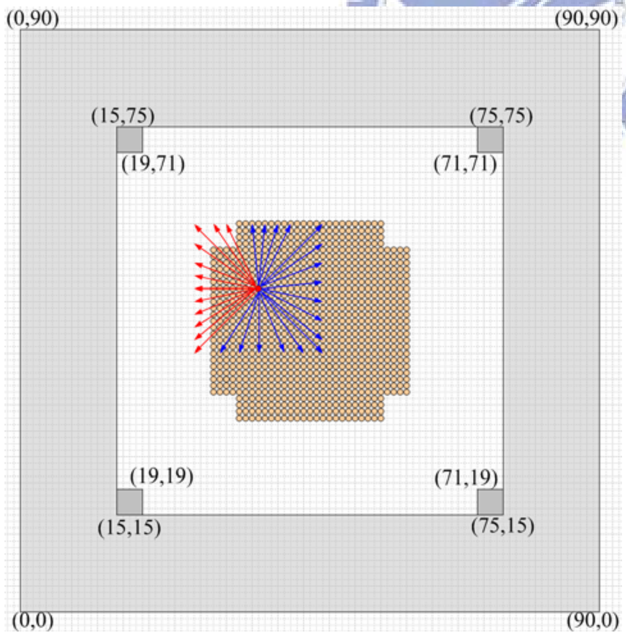


Fig. 6-8 All velocities of a state in wandering region

In Section 6.2.2, we had explained the smart elimination shown as Fig. 6-6, the smart elimination only considers the all possible velocities of a state which can make the location of next state is not in wandering region. The overhead of smart elimination is that we have to find out the all possible velocities of a state in advanced. If we don’t want to pay the overhead for finding out the all possible velocities of a state in advanced, we can directly consider all velocities of a state, but we will check more redundant states. An example of all velocities of a state is shown as Fig. 6-8.

6.2.4 Issue： Unrealistic Cases

In Section 6.2.2, we had explained the approximately equivalent partial verification procedure. The reason why we emphasize the keyword “*approximately*” is that the size of partial verification procedure is greater than or equal to the size of the parts of full verification procedure marked with solid circle. Because some checking cases are not in the parts of full verification procedure marked with solid circle, the approach for eliminating parts of full verification procedure has to handle some overhead for these unrealistic cases. The reason why the result still has great improvement is that the number of states saved by eliminating parts of full verification procedure marked with dotted circle are much more than the number of states produced by unrealistic cases.

6.3 Coarse Sampling of States

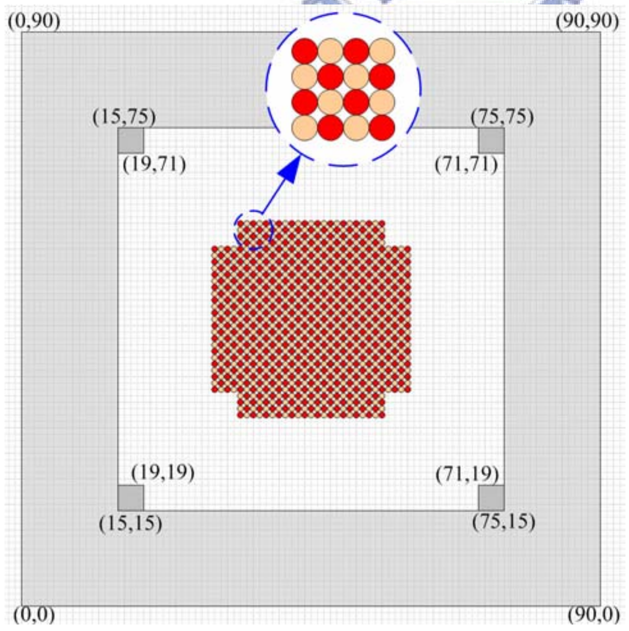


Fig. 6-9 Only half points of wandering region will generate random acceleration

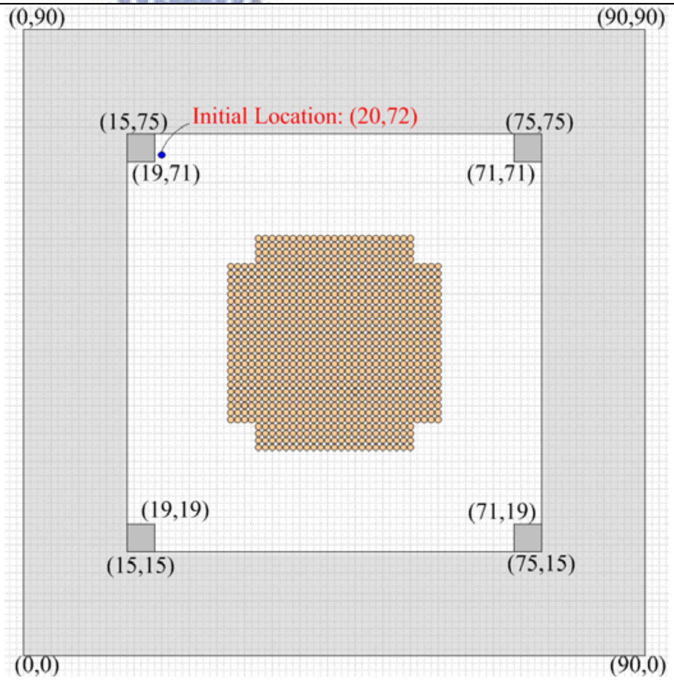
In the experiment, it’s not necessary to generate random acceleration every round while the robot moves into the wandering region. We can simulate the situation by only generating random acceleration at half points of wandering region. It will make the frequency of generating random acceleration in wandering region reduces to 50%.

In Section 6.2.1, we had referred to that the number of all reachable states greatly grows up while the robot moves into wandering region. Therefore, to lower the frequency of generating random acceleration in wandering region will reduce the number of all reachable states of the experiment.

6.4 Checking Results of the Experiment Applied Different Approaches

In this section, we will show the checking results of the experiment applied different approaches. We discuss four cases applying different approaches to the experiment.

All parameters of the experiment are listed as Table 6-1：

MAP	 (0,90) (90,90) (15,75) Initial Location: (20,72) (75,75) (19,71) (71,71) (19,19) (71,19) (15,15) (75,15) (0,0) (90,0) ● Map size: 60 x 60 (from (15,15) to (75,75)) ● Width of boundary buffer area: 15 ● The obstacles can only expand from 4 corners

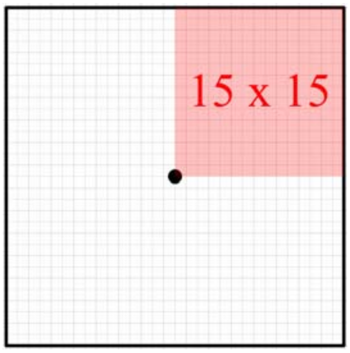
Detection range	
Max Velocity	10
Max Force_Acceleration	7
Max Random_Acceleration	2

Table 6-1 All parameters of the experiment

6.4.1 Case1：Only Apply State Hiding to the Experiment

Description：

In Case1, we only apply state hiding to the experiment by using external function. After completing the verification procedure of checking "No_Collision" property, OMocha proves the property "No_Collision" satisfies the behaviors of the robot. In the results, the number of all reachable states reduces to 27307377, and the checking time is 889 minutes.

Results：

"No_Collision" property	Satisfy
Number of all reachable states	27307377
Checking time (minutes)	889

6.4.2 Case2：Apply State Hiding and Partial Elimination of Checking Cases

Description：

In Case2, we apply state hiding and partial elimination of checking cases to the experiment. In the results, the number of all reachable states is 25129982, and the checking time is 62 minutes. We can observe that to apply partial elimination of checking cases to the experiment will not obviously reduce the number of all reachable states, but the checking time greatly reduces to 62 minutes.

Results：

"No_Collision" property	Satisfy
Number of all reachable states	25129982
Checking time (minutes)	62

6.4.3 Case3：Apply State Hiding and Smart Elimination of Checking Cases

Description：

In Case3, we apply state hiding and smart elimination of checking cases to the experiment. We can expect the results will be better than Case2, because smart elimination can eliminate more checking cases than partial elimination, and the results are consistent with our expectation. In the results, the number of all reachable states is 12850105, and the checking time is 35 minutes. The unrealistic cases are 89.5 % of all checking cases.

Results：

"No_Collision" property	Satisfy
Number of all reachable states	12850105
Checking time (minutes)	35

All checking cases	177188
Checking cases in full verification procedure	158654
Unrealistic cases (%)	89.5

6.4.4 Case4：Apply State Hiding and Coarse Sampling of States

Description：

In Case4, we apply state hiding and coarse sampling of states to the experiment. In the results, the number of all reachable states is 14722810, and the checking time is 489 minutes. The results are only better than Case1, and much more inefficient than Case2 and Case3.

Results：

“No_Collision” property	Satisfy
Number of all reachable states	14722810
Checking time (minutes)	489

6.5 Analysis

***Observations*：**

(1) In all cases, the “No_Collision” property satisfy the behaviors of the AFSM-based RRCS

(2) The number of all reachable states reduces greatly by using smart elimination of checking cases.

(3) By observing the relationship between the results of Case1 and Case3, we can find that the improvement of the checking time is greater than the improvement of the number of all reachable states.

(4)In case3, the checking time of verification procedure is the best of the four cases. The performance is still reasonable after using state hiding and smart elimination of checking cases. It proves that formal verification is applicable for an AFSM RRCS.

***Explanation*：**

(1)： For observation (1)

The two approaches State hiding and eliminating some checking cases don’t change the behaviors of the RRCS. They just reduce the number of all reachable states of the RRCS checked by OMocha.

(2)： For observation (2)

The set of checking cases is chosen according to the behaviors of the RRCS, we can make sure that the set includes all meaningful parts of verification procedure. Therefore, we won’t miss any meaningful parts of verification procedure, and the percentage of redundancy is very low.

(3)： For observation (3)

During verification procedure of OMocha, the possibility of tracing an old state is rising continuously. Therefore, the growing rate of tracing new states is decreasing continuously.

<u>Summary</u> **：**

	Approach1	Approach1,2	Approach1,3	Approach1,4
Results	27307377(889)	25129982(62)	12850105(35)	14722810(489)

Table 6-2 Checking results comparison

(Approach1：State hiding

Approach2：Partial elimination of checking cases

Approach3：Smart elimination of checking cases

Approach4：Coarse Sampling of States)

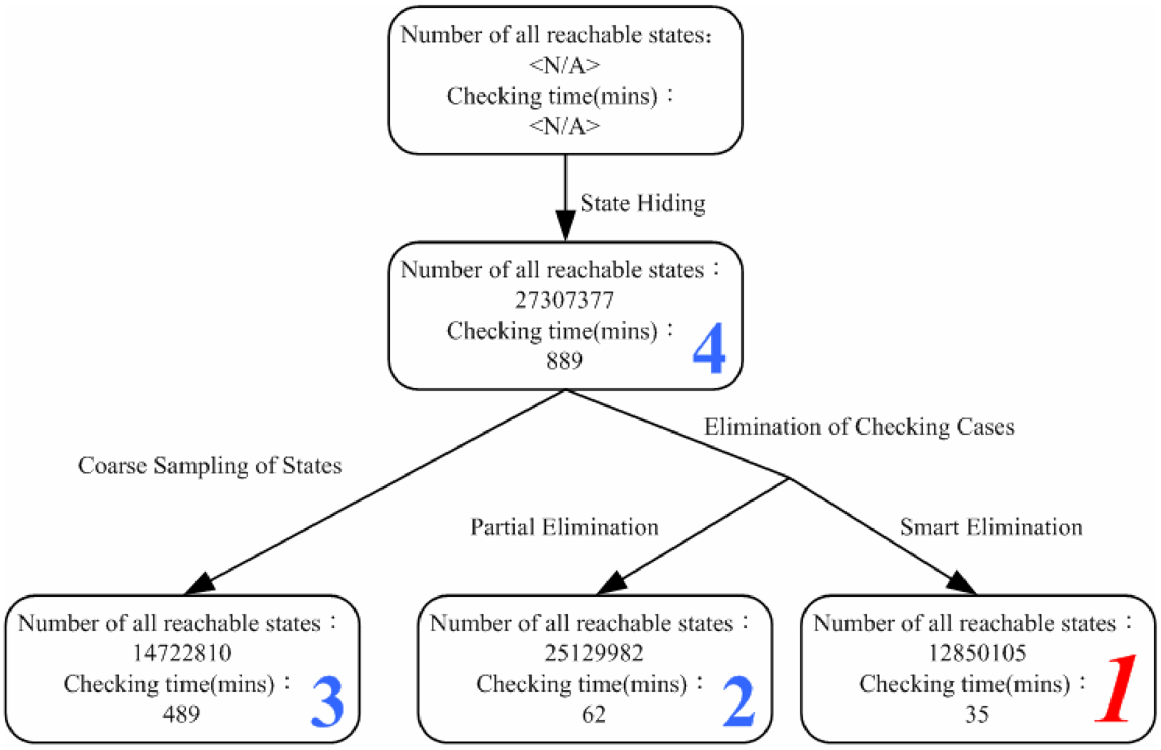

Number of all reachable states:
<N/A>
Checking time(mins)：
<N/A>
State Hiding
Number of all reachable states：
27307377
Checking time(mins)：
889
4
Coarse Sampling of States
Elimination of Checking Cases
Partial Elimination
Smart Elimination
Number of all reachable states：
14722810
Checking time(mins)：
489
3
Number of all reachable states：
25129982
Checking time(mins)：
62
2
Number of all reachable states：
12850105
Checking time(mins)：
35
1

Fig. 6-10 Checking results comparison2

In case1, we can make sure the robot won't collide with walls or obstacles through property checking, but the performance of verification procedure is not good enough to handle more complicated system.

After using smart elimination of checking cases in case3, the number of all reachable states and checking time improve greatly (27307377(889mins)→ 12850105(35mins)) . Therefore, the performance of verification procedure becomes more reasonable.

Chapter 7
Conclusion

7.1 Accomplishment

In this thesis, we reach two accomplishments listed below：

(A) Check the Behaviors of the AFSM-based RRCS by Model Checker

After rebuilding the AFSM-based RRCS by UNITY-based specification language, we describe the “No Collision” property by Temporal Logic, and check whether the behaviors of the RRCS satisfy the property by model checker, OMocha. After verification procedure completed by OMocha, we can make sure the robot will never collide with obstacles or walls in two-dimensional environment.

(B) Improve the Performance of Verificaiton Procedure

Although we had proved the robot will never collide with obstacles or walls, the performance of verification procedure is not efficient enough, and it spends (> 889) minutes checking the “No Collision” property for the experiment. In order to improve the performance of verification procedure, we present three approaches to reduce the checking time of verification procedure. The three approaches are：(1) Using external function for state hiding, (2) Elimination of unnecessary checking cases, and (3)Coarse sampling of states. After reducing the checking time by the three approaches, the best results show that the verification procedure can be completed in 35 minutes.

7.2 Future Work

Based on the accomplishments of this thesis, there are still some objectives can be researched in the future. They are listed below：

(A) Build a more complicated AFSM-based RRCS and Check its Behaviors

We can construct a more complicated AFSM-based RRCS. The modules of the RRCS have more complicated functionalities written by external function. For example, we can construct a GOAL module to guide the robot to the specific destination. After constructing the more complicated RRCS, we check the properties of the RRCS by OMocha, and look whether the performance of verification procedure is still reasonable and has practicability.

(B) Develop the Tools for Constructing and Checking AFSM-based RRCS

In our research, we spend much time on constructing RRCS and revising verification procedure manually. If we want to encourage RRCS designers to use our methods for constructing and checking RRCS, we have to develop the tools which can make the procedure of constructing and checking an AFSM-based RRCS more easily. RRCS designers can combine some modules which are in library to construct an AFSM-based RRCS, and select the properties they want to check.

(C) Design the Real Robot controlled by AFSM-based RRCS

We can implement the AFSM-based RRCS introduced in Section 5.1 on a real robot, and look over whether the real robot can wander aimlessly around the environment without colliding with obstacles.

Reference

[1] R.A. Brooks, “A robust layered control system for a mobile robot”, *IEEE J. Rob. Autom.* 2(1986) 14-23

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[3] Fabio Somenzi. "Binary Decision Diagrams". In Manfred Broy and Ralf Steinbruggen, editors, Calculational System Design, volume 173 of NATO Science Series F: Computer and Systems Sciences, pages 303--366. IOS Press, 1999.

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[5] Merz, Stephan, *Model Checking: A Tutorial Overview*. Institut fur Informatik, Universitat Munchen, 2001.