The model construction and implementation of discrete physical system in industrial CPS

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Received 20 June 2014, www.cmnt.lv

Abstract

Cyber physical system referred as CPS, or information physical system, achieves the integrated coordination of the cyber world and the physical world. The collaborative system is more reliable and efficient. By analyzing the cyber physical system of integrated sense and control, the constructing approach of the discrete physical model is proposed and applied to mine surface production systems for CPS of the combination of discrete-time input and output and control functions. By modelling, analyzing and verifying the system, the cyber system and the physical system achieve deep fusion. On this basis, trusted software design, formal description methods and reasoning theory are established in the cyber physical system. It provides the authentication methods for the trusted software analysis and modelling of discrete physical system in the cyber physical system. The coal surface production system model is established by the model construction method of discrete physical systems in CPS proposed in this paper. The technology of computer, computer network and embedded systems is adopted to build the information world and achieve the integrated design and collaborative control of the subsystem in CPS. It is applied in a coal mine in the Huaibei Coal Mine Shares Limited Company and achieves good results. To speed up the wide applications to industries and enterprises of the CPS, a useful exploration is carried out in the paper.

Keywords: information world, physical world, discrete physical system, information fusion, credible design

1 Introduction

Cyber physical system is a complex system integrated the information processing technology and physical environment. It is an integrated system of the physical process and the calculation process. Cyber physical system achieves wisdom perception, real-time control and interactive services in the industrial and mining engineering system through the further integration of computing, communications and controlling. Information physical fusion system achieves the integrated design of the information world and the physical world and makes the cooperative system more reliable, efficient [1]. In recent years, information physical fusion system has become an important direction of research and development in the academic and scientific fields, has also become a priority development industry in industrial mining field. It is of great significance for accelerating China's industrialization and information fusion to carry out the research and application of physical information fusion system [2].

Due to security and other requirements, application technology of coal mine enterprises is very advanced in our country. Accordingly, information physical fusion system is more suitable for large-scale enterprises such as mine. It has multiple productions, transportation and other systems. Each system includes sensors, actuators, control unit, etc. and has many parameters detected and controlled and has also many corresponding system status parameters. Thus, mine information physical fusion system is very large. It is difficult to analyse it from the whole system. As we all know, any a complex system, is a combination of multiple simple systems [3]. Mine information physical fusion systems is also true. Therefore, build and combine the coal production system, transportation system and each other subsystems to complete the entire mine information physical fusion system [4].

In this paper, on the base of the analysis of construction method of information physical fusion system model having the discrete-time input, output combination and control, select a ground mine production system as an example. Through an analysis of the modelling method and verification method of the physical system, fuse it with the information world and establish a kind of software credible design method, research method, formal description method and reasoning theory for the coal information physical fusion system. It provides mathematical models and verification means for trusted software system analysis and model study of the coal information physical fusion system and constructs the software physical theories and methods for the application of information to ensure that information physical fusion system fidelity and faithful implementation. It utilizes industrial control computer, embedded system and computer network to control the

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ground production system of a mine in Huaibei Coal Mine Company.

2 Discrete physical system model building approach in CPS

In industrial and mine enterprises, so many physical systems have the integration function with discrete time input and output combination, sensing and controlling.

As a discrete event occurs in an instant, rather than continuously changes over time. Thus, the signal in discrete system has a functional form as follows: signals: R {absent, present}, t∈R [5].

For discrete physical system, we use a five element finite state to represent it as follows.

(States, Inputs, Outputs, Updates/Possible updates, Initial State) of which:

States: a finite set of the stations in the system.

Inputs: input signal set in the system.

If a discrete system has N input ports P = {P1, P2, ... ,PN}, and each port p∈P has a corresponding type Vp, the system input signal set Inputi: P Vpi∪…..∪VpN∪{absent}, for each p∈P, Inputi(P)∈Vp∪{absent}.

Outputs: system output value set.

Updates: an upgrade function, thought it a state and an input value are mapped to the next state and the output value set. States × Inputs States × Outputs, Possible updates map the state and an input value to the next possible state and the output value set. Namely, States×Inputs 2States×Outputs.

Assume S: N States, is a function. at the same time, assume S(0)= initialState0,(x0,y0) to be initial input and output. The system trajectories (x, si, yi) (i=0, 1, 2, 3…) including the state is all the state trajectories tracked of the discrete system [6-7].

In the case of the input x: N Inputs, status S: N States, output y: N Outputs, get the discrete-time system model:

$$(S(n+1), y(n)) = Update(S(n), x(n)) / Possible\ Update(S(n), x(n)) . \quad (1)$$

3 Mine ground production system components, operation mode and function

Mine ground production system is composed of a multi-belt conveyor, multiple coal feeders, vibrating screen, pumps and other components. It is a kind of key transport equipment in the course of coal production. Generally, it is set a few hundred meters in length. In addition to maintenance, one day it runs for at least 22 hours. It is the vital lifeline of mine. Normal production of the entire coal mine is related to safe operation.

The main function of surface production system is to control the four coal feeders, vibrating screen, the main belt, hand-selected belt, something blending belt, floor belt, back to the coal belt and water pump. The system does not affect the original manual control operation. It realizes remote monitoring through information physical fusion system and the computers in the dispatching control center. The remote computers real-time display the motion state of coal feeders, vibrating screen, the main belt, hand-selected belt, something blending belt, floor belt, back to the coal belt, water pump, can achieve the remote control.

The system's control is in three ways, respectively: linkage mode, independent manner and maintenance mode. At the same time, there are emergency stop and a variety of protection function in the system.

A. Linkage Mode

By linkage mode, computer operation can start in sequence No.1,2 coal feeder, vibrating screen, the main belt, hand-selected belt, something blending belt, belt landing. Startup sequence is: 1) Start stuff blending belts, floor belt; 2) start the main belt; 3) Start the belt hand-selected and shaker; 4) North and South coal feeder. There is a ten second delay between each step. And before starting, detect the situation of heap coal and motor current. Start operation will fail if heap coal and overcurrent occurs.

By the way, of linkage mode, No. 1, 2 coal feeder, vibrating screen, the main belt, hand-selected leather belt, something blending belt, belt landing can be stopped in sequence. Stop order is: 1) Stop the coal feeder; 2) Stop the belt hand-selected and shaker; 3) Stop the main belt; 4) Stop things blending belts, floor belt. There is a ten seconds delay between each step.

When needed, add the control to back to the coal belt, No.1, 2 floor coal feeder. Back to the coal belt, No.1, 2 floor coal feeder, pumps, etc. can also be controlled independently.

B. Independent Manner

By the way of independent manner, console and computer can both control the start and stop of a single device, and can be any combination of the start and stop, in other words, console controls the start-up. Computer controls hut-down. Computer controls start-up. Console controls hut-down. Computer controls start-up and hut-down.

By this manner, two coal feeders, vibrating screen, the main belt, hand-selected belt, something blending belt, the floor belt, back coal belt, water pump and North and South floor coal feeder are controlled by the computer independently. Before starting, detect the situation of heap coal and motor current. Start operation will fail if heap coal and overcurrent occurs.

C. Maintenance Mode

By maintenance mode, operation and independent control is basically the same way. The difference is that heap coal and motor overcurrent condition need not be detected before driving by the way of maintenance mode. If heap coal or overcurrent occurs, the operation also can be carried out and drive.

D. Emergency Stop

If system accidents happen in running state, press the “stop” button (emergency stop) (It lies in both on-site and computer control interface of control center). At this time no matter what state each equipment of the system is, will be forcibly stopped. System immediately stops.

E. System Protection Function

Ground production system has function of heap coal protection. When coal accumulation exceeds a certain height, the system sends heap coal signal, and system is stopped and processed. The system is with overcurrent protection. When the motor current exceeds the set value, the system sends an overcurrent signal and stops to reliably protect the motor.

System also has the function of belt deviation protection, interlock protection, back-tested protection, blocking protection, under voltage protection.

Ground production system structure is shown in Figure 1.

FIGURE 1 Ground production system

4 Model construction of ground production system model

Through analysis of the ground production system, get its input, output, and status signals as follows:

1) Input signal

Independent linkage control I0
Emergency stop (stop) I1
Overhaul state detection I2
Overcurrent detection I3
Heap coal state detection I4
Main belt running monitoring I5
Coal gangue belt running monitoring I6
No.1 coal feeder running monitoring I7
No.2 coal feeder running monitoring I8
No.1 coal blending belt running monitoring I9
No.2 coal blending belt running condition monitoring I10
Floor belt running monitoring I11
Clean water pumps running detection I12
Sewage pumps running state detection I13
No.1 return coal feeder running monitoring I14
No.2 return coal feeder running monitoring I15
Vibrating screens running monitoring I16
Vibrating screens with or without coal monitoring I17
Stop I18
Bunker full of coal detection I19
Back coal belt running detection I20
Main belt start signal detection I25
Coal gangue belt start signal detection I26
No.1 coal feeder start signal detection I27
No.2 coal feeder start signal detection I28
No.1coal blending belt start signal detection I29
No.2 coal blending belt start signal detection I30
Floor Belt start signal detection I31
Clean water pumps start signal detection I32
Sewage pumps start signal detection I33
No.1 back coal feeder start signal detection I34
No.2 back coal feeder start signal detection I35
Vibrating screens start signal detection I36
Back coal belt start signal detection I40

2) Output Signal

Main belt output control Q0
Coal gangue belt output control Q1
Vibrating screens output control Q2
No.1 coal feeder output control Q3
No.2 coal feeder output control Q4
No.1 coal blending belt output control Q5
No.2 coal blending belt output control Q6
Floor Belt Output Control Q7
No.1 return coal feeder output control Q8
No.2 return coal feeder output control Q9
Clean water pumps output control Q10
Sewage pumps output control Q11
Return coal belt Q12 output control

3) Status Signal

S0, S1, S2, S3, S4, S5, S6-1, s6-2, S7, S8-1, S8-2

Therefore,

Input signals= {I0, I1… I40}

Output signals= {Q0, Q1…Q12}

State signals= {Ss, S0, S1…S8-2, Se}

Based on the system composition, operation principle and technological process get the running state transformation diagram shown in figure 2.

The figure 2 shows that in the initial state press the linkage Run button, system will run by the way of computer remote control and the state changes from Ss to state S0. Under the state S0, if the system meets the condition of the linkage mode, not pressing emergency stop (stop) button, not in the way of maintenance mode, not detecting an overcurrent condition and heap coal conditions and other conditions, the system will enter the S1 state after the 10-second delay. The system will also change to the S1 state in the case of not the linkage mode, detecting No. 1 coal blending belt start signal and the NO.2 coal blending belt start signal. After the system changes to the S1 state, start No.1 and No.2 blending coal belt. And According to system operating mode and p process, turn into the corresponding state and control the corresponding controlled object.

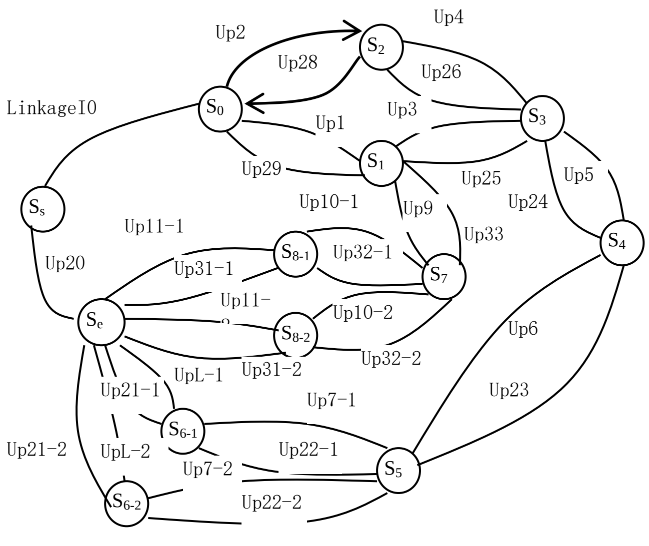

FIGURE 2 Transformation state of system

Thereby the system state transition relations and output control model are as follows:

$$\begin{array}{l} Updates1\_inputs=[I0(not)I1(not)I2(not) \\ I3(not)I4(not)I19F(t+10)] \\ [(not)I0I29I30](S0,\ Updates1\_inputs) \\ -->\ (S1,Q5,Q6) \end{array}, \quad (2)$$

$$\begin{array}{l} Updates2\_inputs= \\ [I0(not)I1(not)I2(not) \\ I3(not)I4(not)I19F(t+10)] \\ [(not)I0I31](S0,\ Updates2\_inputs) \\ -->\ (S2,Q7) \end{array}, \quad (3)$$

$$\begin{array}{l} Updates3\_inputs=[I0(not)I1(not)I2(not) \\ I3(not)I4F(t+10)I9I10][(not)I0I25] \\ Updates4\_inputs=[I0(not)I1(not) \\ I2(not)I3(not)I4F(t+11)I10] \\ [(not)I0I25](S1,\ Updates3\_inputs) \\ (S2,\ Updates4\_inputs)-->\ (S3,Q0) \end{array}, \quad (4)$$

$$\begin{array}{l} Updates5\_inputs=[I0(not)I1(not)I2(not) \\ I3(not)I4(not)I19F(t+10)I5] \\ [(not)I0I26](S3,\ Updates5\_inputs) \\ -->\ (S4,Q1) \end{array}, \quad (5)$$

$$\begin{array}{l} Updates6\_inputs= \\ [I0(not)I1(not)I2(not)I3(not) \\ I4(not)I19F(t+10)I6][(not)I0I36] \\ (S4,\ Updates6\_inputs)-->\ (S5,Q2) \end{array}, \quad (6)$$

$$\begin{array}{l} Updates7-1\_inputs= \\ [I0(not)I1(not)I2(not) \\ I3(not)I4(not)I1F(t+10)I6] \\ [(not)I0I34](S5,\ Updates7\_inputs) \\ -->\ (S6,Q3) \end{array}, \quad (7)$$

$$\begin{array}{l} Updates7-2\_inputs= \\ [I0(not)I1(not)I2(not) \\ I3(not)I4(not)I19F(t+10)I6] \\ [(not)I0I35](S5,\ Updates7\_inputs) \\ -->\ (S6,Q4) \end{array}, \quad (8)$$

Updates8-1_inputs=const
Updates8-2_inputs=const

$$\begin{array}{l} (S6-1,\ Updates8-1\_inputs) \\ (S6-2,\ Updates8-2\_inputs)-->\ (Se,none) \end{array}, \quad (9)$$

$$\begin{array}{l} Updates9\_inputs= \\ [I0(not)I1(not)I2(not) \\ I3(not)I4(not)I19F(t+10)(not)I1I10] \\ [(not)I0I40](S1,\ Updates9\_inputs) \\ -->\ (S7,Q12) \end{array}, \quad (10)$$

$$\begin{array}{l} Updates10-1\_inputs= \\ [I0(not)I1(not)I2(not) \\ I3(not)I4(not)I19F(t+10)(not)I1] \\ [(not)I0I34](S7,\ Updates10-1\_inputs) \\ -->\ (S8,Q8) \end{array}, \quad (11)$$

$$\begin{array}{l} Updates10-2\_inputs= \\ [I0(not)I1(not)I2(not) \\ I3(not)I4(not)I19F(t+10)(not)I17]I20 \\ [(not)I0I35](S7,\ Updates10-2\_inputs) \\ -->\ (S8,\ Q9) \end{array}, \quad (12)$$

Updates11-1_inputs=const
Updates11-2_inputs=const

$$\begin{array}{l} (S8-1,\ Updates11-1\_inputs) \\ (S8-1,\ Updates11-2\_inputs), \\ -->\ (Se,none) \end{array} \quad (13)$$

$$\begin{array}{l} Updates20\_inputs= \\ I0I18(Ss,\ Updates20\_inputs)-->\ (Se,none) \end{array}, \quad (14)$$

$$Updates21-1\_inputs = [I0I18(not)I17F(t+10)]I1 [(not)I0(not)I27](Se,\ Updates21-1\_inputs), --> (S6-1,(not)Q3) \quad (15)$$

$$Updates21-2\_inputs = [I0I18(not)I17F(t+10)]I1 [(not)I0(not)I28](Se,\ Updates21-2\_inputs), --> (S6-2,(not)Q4) \quad (16)$$

$$Updates22-1\_inputs = [I0I18(not)I7F(t+10)]I1[(not)I0(not)I36] \quad Updates22-2\_inputs = [I0I18(not) I8F(t+10)]I1[(not)I0(not)I36], (S6-1,\ Updates22-1\_inputs) (S6-2,\ Updates22-2\_inputs) --> (S5,(not)Q2) \quad (17)$$

$$Updates23\_inputs = [I0I18(not)I16F(t+10)]I1 [(not)I0(not)I26](S5,\ Updates23\_inputs), --> (S4,(not)Q1) \quad (18)$$

$$Updates24\_inputs = [I0I18(not)I6F(t+10)]I1 [(not)I0(not)I25](S4,\ Updates24\_inputs), --> (S3,(not)Q0) \quad (19)$$

$$Updates25\_inputs = [I0I18(not)I5F(t+10)]I1 [(not)I0(not)I9(not)I20] \quad Updates31-1\_inputs = [I0I18F(t+10)]I1[(not)I0(not)I34], (Se,\ Updates31-1\_inputs) --> (S8-1,(not)Q8) \quad (20)$$

$$Updates31-2\_inputs = [I0I18F(t+10)]I1[(not)I0(not)I35] (Se,\ Updates31-2\_inputs), --> (S8-2,(not)Q9) \quad (21)$$

$$Updates32-1\_inputs = [I0I18F(t+10)(not)I14]I1 [(not)I0(not)I40](Se,\ Updates31-1\_inputs), --> (S8-1,(not)Q8) \quad (22)$$

$$Updates32-2\_inputs = [I0I18F(t+10)(not)I15]I1 [(not)I0(not)I40]\ (S8-1,\ Updates32-1\_inputs), (S8-1,\ Updates32-1\_inputs) --> (S7,(not)Q12) \quad (23)$$

$$Updates33\_inputs = [I0I18F(t+10)I1 [(not)I0(not)I9(not)I10], (S3,\ Updates25\_inputs)(S7,\ Updates33\_inputs) --> (S1,(not)Q5,(not)Q6) \quad (24)$$

$$Updates26\_inputs = [I0I18F(t+10)(not)I5]I1 [(not)I0(not)I11](S3,\ Updates26\_inputs), --> (S2,\ (not)Q7) \quad (25)$$

Updates27_inputs=const
Updates28_inputs=const

$$(S1,\ Updates27\_inputs) (S2,\ Updates28\_inputs) --> (S0,\ none). \quad (26)$$

The above model is easy to realize through the remote computer and embedded microcontroller processor.

5 Analysis of the reachability and model verification of the system state

A. Linear Temporal Logic

For the accessibility and accuracy verification of the above system model, we introduce the linear temporal logic to analyse it. Linear temporal logic is able to clearly express the occurrence of an event and its properties, the causal relationship between events and their sequence [8]. First we introduce the execution trace Et. Execution trace is a sequence. It reflects the execution process, which is expressed as: Et_0, Et1, Et2 …

Among them, $Et_i= (x_i,s_i,y_i)$. X_i, s_i and y_i respectively represent input, state, and the output value of the ith.

A linear temporal logic formula applies to all execution traces Et_0, Et_1, Et_2...of the whole system [9]. We use Fm_0, Fm_1, Fm_2 to represent the linear temporal logic formula and use Pp_0, Pp_1 and Pp_2, etc. to represent the thesis in the model.

For the state model Ms and the corresponding linear temporal logic formula Fm, if Fm is right for all the possible execution trace Et of the system model, Fm is right for the Ms.

To better reasoning out the whole trace of a state model of, then we introduce some temporal operator in the linear temporal logic.

Global operator Gl (Fm)

If the linear temporal logic formula Fm is true for a track and all the following tracks, then the property Gl (Fm) is true for this track.

Final operator Fi (Fm)

If the linear temporal logic formula Fm is true for a following track, then the property Gl (Fm) is true for this track.

Later state operator Nx (Fm)

If the linear temporal logic formula Fm is true for the path Et0, Et1, Et2 ... in state model, then the property Nx (Fm) is true for this track.

Until operator (Fm1) Un (Fm2)

If the linear temporal logic formula Fm1 is true for a track after a track and Fm1 maintains until Fm2 is true, then the property (Fm1) Un (Fm2) is true for this track.

With the above definition, we can have an analysis of an infinite number of events of state model Gl (Fi) (Fm), state stability Fi (Gl (Fm)) and request response properties Gl (Pp=>Fi (Et)) and so on to.

B. Accessibility Analysis

To verify and analyse this system is to verify system model and the enclosed model composed of the environment model of the system [10-11]. Therefore, the verification process has three input signals. They are respectively validation system model S, environment model E and the properties Fm to be verified. The validator will create a Yes/No output result. Model validation process is shown in Figure 3.

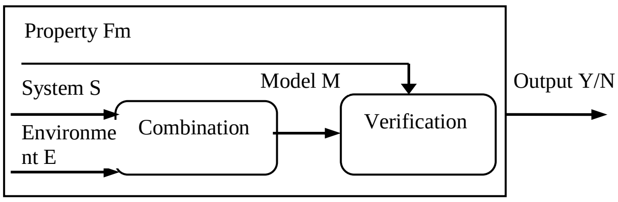

FIGURE 3 Model validation process

Through the analysis of the ground production system environment, the ground production system environment model is shown in figure 4. The environmental information includes mainly man-machine dialogue, hoisting system, transportation system, storage system etc.. Due to limited space, the paper has no its in-depth analysis.

The relationship between the ground production system environment model and the ground production system model is shown in figure 5.

For a state model Ms and the attribute Fm is the linear temporal logic formula in the form of Gl (Pp) (Pp is a proposition). When p is true for each state in a track, Gl (Pp) is a linear temporal logic formula in this trajectory.

To make the system state models Ms meet it, each listed track of the system state model Ms must meet the Gl (Pp).

FIGURE 4. Environment model of ground production system.

Next we prove the accessibility of surface production system model through enumeration method.

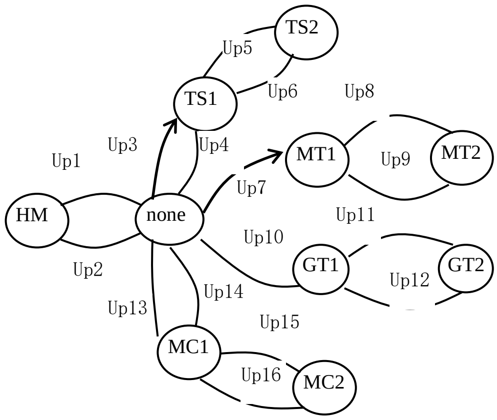

FIGURE 4 Environment model of ground production system.

To be verified closed system Mm composed of the system model Ms and environment model Me are an uncertain system with finite state and no input. The next state sets are only related to the current state. This relationship is described by the function denoted by Tr. So Tr is the next set of possible states of the state s of Mm.

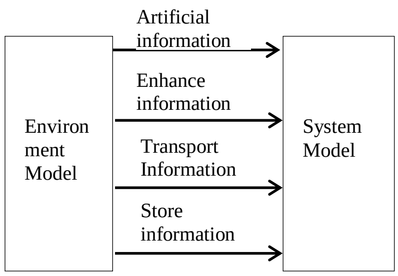

FIGURE 5 The ground production system environment model and the ground production system model

Adopting depth-first traversal, by constantly using Tr to dynamically generate state diagram for the access state. Computing the state set that Mm can achieve. The algorithm is as follows:

```
    Input
    Output
    Initialize
    DepthFirstTraversal()
    {
    while Stack Sall is not empty do
  pop the state s at the top of Sall
  compute Tr(s)
  for each ss ∈ Tr(s) do
              if ss not ∈ R then
                     R:=R ∪ {ss}
                     Push ss onto Sall
                     DepthFirstTraversal()
```

```
            End
        End
    End
    }
```

Program calls the algorithm and completes, the set R is all accessible state set of Mm.

The storage space and running time of the above algorithm is proportional to the state number of the Mm. The number of state in the system Mm is index times of the size of the set Ms and set Me. For the system (figure), it is mainly the discrete system, if we take time t as the change quantity and seconds as unit to calculate the number of state, the Ms alone has 121 Boolean state variables, coupled with nine of Me, the Mm has 130 Boolean state variables total and 2130 states. So, it has a large amount of data far more than the general computer storage capacity. For this, the above algorithm need be improved.

The above algorithm detects the accessibility for each individual state which produces a large amount of data. If we adopt the special data structures to test a state set only, it can greatly reduce the calculation. The improved algorithm is as follows:

```
Input
Output
Initialize
StateSetSearch ()
{
Rnew=R
while Rnew != 0 do
    Rnew = {s| ∃ss ∈ Rs.t.s ∈ Tr(ss)}
    R: =R ∪ Rnew
end
}
```

In the algorithm StateSetSearch, the set R is the whole set of all the state which can reach and be searched. Rnew represents the new state generated by those points. When there is no new status, the algorithm stop. At this time, all of the states which can reach from S0 are put in the set R.

Use algorithm StateSetSearch to analyse the reachability of the ground production system model, get the reachability state set. The correctness of the model is verified by the set.

6 Conclusion

Information physical system is not a simple combination of information system and physical system, but the all-round and multi-level depth fusion and integration. It is a kind of self-sensing system. It is a kind of new system, which consists of a large number of sensing devices, computing devices and communication networks. These characteristics make it more suitable for the production and management of industrial and mining enterprises. Information physical system is huge and it is very huge for the information physical system of an industrial and mining enterprise. It contains a number of technology and rich resources, which has not been well studied and applied. In the course of researching and developing the ground production monitoring system in coal mine, the author try to adopt the integration idea, information physical system, to achieve wisdom awareness, real-time control and interactive services. As an actual subsystem of information physical system applied in the field of industrial and mining enterprises, this article has an analysis of the model building method of the common discrete physical system in information physical systems in industrial and mining enterprises firstly. Then, according to the input, output, and the technology in the mine surface production system the system model is constructed. In order to ensure the accessibility and the correctness of the model, the author has established the discrete physical system model, its reliable software design, the formal description method and the reasoning theory in information physical fusion system. It provides validation method for the reliable software analysis and modelling in the discrete physical system of information physical fusion system. The study will accelerate the development of industrial and mining enterprises information physical system. The next step we will put more system in it.

Lastly, the mine surface production system model is established by the model building method of discrete physical system in the industrial CPS proposed in the paper. And computer network and embedded system are used to construct the information world and implement the CPS subsystem design and the cooperative control as an organic whole. The system has been applied to Yang Zhuang coal mine in Huaibei Coal Mining Shares Limited Liability Company. Good results have been achieved.

Acknowledgements

This work is supported by Anhui Provincial Natural Science Foundation of Universities Key Projects (Grant No. KJ2010A083) , the Natural Science Foundation of the Anhui Higher Education Institutions of China (KJ2012A099),and is also supported by the National Natural Science Foundation of China (Grant No. 51174257) and Yong Backbone Teachers of Anhui University of Science and Technology.

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