UNIVERSITÄT AUGSBURG

The Statemate Reference Model of the Reference Case Study ‘Verkehrsleittechnik’

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Report 2002-1 Januar 2002

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Abstract

The German railway organization, Deutsche Bahn, prepares a novel technique to control level crossings: the dezentralized, radio-based level crossing control. We present a model of this application with activity- and statecharts developed in STATEMATE[1]

The model described in this paper has been developed within the DFG (Deutsche Forschungsgemeinschaft/German Research Foundation) focus area program *Integration von Techniken der Softwarespezifikation für ingenieurwissenschaftliche Anwendungen*[2] (Integration of Software Specification Techniques for Engineering Applications). The application modeled here is one of the two reference case studies which are provided by this focus area program in order to be able to compare the results of the individual projects. The modelling has been carried out by the projects USE and FORMOSA, other projects (SafeRail and KNOSSOS) have been involved in discussions and in resolving detailed questions about the problem domain.

The case study describes the interaction between trains and level crossings in a radio-based signaling system (funkbasierter Fahrbetrieb, FFB). In order to keep the model sizes manageable several versions of the case study are scheduled. The model presented here has been developed according to the first, simplest version. It implements the control procedure corresponding to the so called ÜS-Prinzip, i.e. the train requests the securing of the crossing and after a certain delay sends another message requesting the status of crossing. This minimal version only considers a restricted set of crossing types:

- single crossings, i.e. an interleaving of two or more securing procedures is not covered.
- single track crossings

In order to further simplify comparing different approaches and techniques the creation of this reference model has been initiated. Even though there exists a reference case study this still allows differring interpretations concerning the details. The reference model presented here has been designed to provide all interested individual projects with a uniform basis for their particular approach. Therefore

[1] STATEMATE is a registered trademark of i-Logix Inc.

[2] `http://tfs.cs.tu-berlin.de/projekte/indspec/SPP/`

we have tried to narrow down the room for different interpretations without making the design too specific, thereby excluding some techniques from the start. We have chosen the Statemate system as a modelling tool, because state charts are used by several projects within the focus area program and it therefore seems to be the most general and useful modelling technique.

1 Overall System Architecture (Activity Chart SYSTEM)

First we start with the description of the general design of our reference model for the radio-based crossing control. It provides an overview over the functions and the correlations between the different activities shown in Fig. 1.

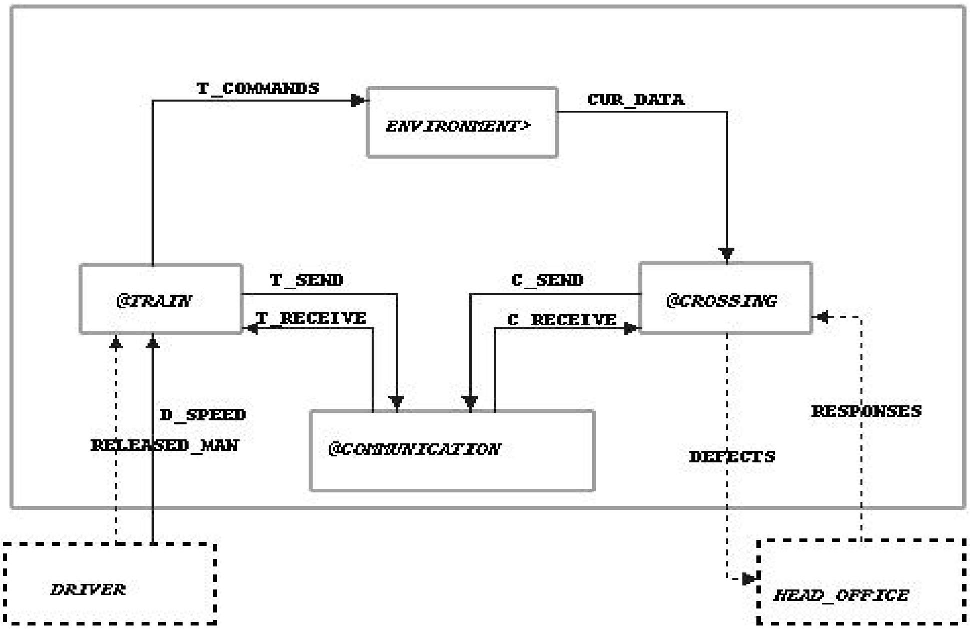


Figure 1: Activity Chart SYSTEM

Having analyzed the requirements on the FFB the separation into six different components has proved to be useful. These are the two main activities TRAIN and CROSSING, the COMMUNICATION between them, the ENVIRONMENT which reflects the real world, and furthermore the 'human components' DRIVER and HEAD_OFFICE, with the latter two not being modeled in detail. The general component SYSTEM consists of these main activities and represents the top level of our model.

The activity TRAIN (see Sect. 4) not fully implements a real train but parts of it which are relevant to the functionality of the FFB. These are the speed control in conjunction with the brake, the odometer for keeping track of the actual position and speed, and the control to enable the crossing.

The implementation of a level crossing in the activity CROSSING (see Sect. 5) contains all its components (the lights, the barrier, a train sensor) and the control units for these components as well as the overall control for closing and opening the crossing.

The physical environment is modeled in the activity ENVIRONMENT (see Sect. 3). Here the position and speed of the train, i.e. the dynamic train data, are described and therefore some calculations have to be made. The environment information is made available to the activity CROSSING via the information flow CUR_DATA. In the direction from ENVIRONMENT to TRAIN there is no data exchange because the train uses the odometer unit to get information about its position and speed, which is modeled independently. In the reverse direction the activity TRAIN passes acceleration data (T_COMMANDS) on to the ENVIRONMENT. Based on this information the speed of the train in the real world is calculated, which thereafter is measured by the odometer in the train.

The information flow between TRAIN and CROSSING is established by means of the COMMUNICATION activity (see Sect. 2). The information exchange takes place via the information flows T_SEND and T_RECEIVE between TRAIN and COMMUNICATION, respectively C_SEND and C_RECIEVE between CROSSING and COMMUNICATION. Thereby the sent signals (in T_SEND/C_SEND) are forwarded by the COMMUNICATION activity within the appropriate receive channel (C_RECIEVE/T_RECEIVE).

The radio communication has to be explicitly enabled and disabled, which is done by the train. Therefore T_SEND also contains the events ST_COMMUNICATION and SP_COMMUNICATION to start and stop the communication which are not sent to CROSSING. The confirmation of the communication establishment (COMMUNICATION_ESTABLISHED) is contained in T_RECEIVE.

All further exchange of information is related to interaction with the staff at the head office (FFB-Zentrale): The DRIVER determines by D_SPEED the desired train speed and may re-start the train after a stop (RELEASED_MAN). Furthermore the HEAD_OFFICE will be informed via DEFECTS about any malfunction regarding the components of the crossing and on its part is in the position to 'repair' these units (REPAIRED) resp. to instruct the software control about the evacuation of the crossing (CROSSING_VACATED) by means of RESPONSES.

For a comprehensive list of the used information flows see Appendix B.

2 Communication

The activity COMMUNICATION represents the radio link between TRAIN and CROSSING. It is explicitly modeled to provide the possibility to simulate errors when establishing the connection and to be able to consider communication delays.

In the current system version it is intended that the train initiates the connection establishment by ST_COMMUNICATION whereupon the control of the radio unit (COMMUNICATION_CTRL) changes into to state WAIT_FOR_CONNECTION (see Fig. 2). This would be the point for possible extensions of the model, in order to model for example the failure of certain communication devices. However at this moment only an 'establishing lag time' (ELT) is considered before the radio connection is ready. When the communication is established an acknowledgement is sent to the train (COMMUNICATION_ESTABLISHED).

The further interactions take place instantaneously, i.e. requests and acknowledgements are passed on directly. Since the radio mechanism is located between TRAIN and CROSSING, sent signals are intercepted by it and passed on afterwards. The original signals in T_SEND resp. C_SEND have thereby the ending _SND which becomes _REC in C_RECEIVE resp. T_RECEIVE on the receiver side.

The interactions are in detail (see Appendix B.1) the communication TRAIN → CROSSING by means of ENABLE_CROSSING to request the securing of the crossing, STATUS_RQ to request a status message, and CROSSING_FREE when the crossing has been vacated by the train. On the other side the communication CROSSING → TRAIN contains the event ACK which acknowledges the receipt of the closing request, and the status message CROSSING_SAFE to indicate that the crossing has been secured successfully.

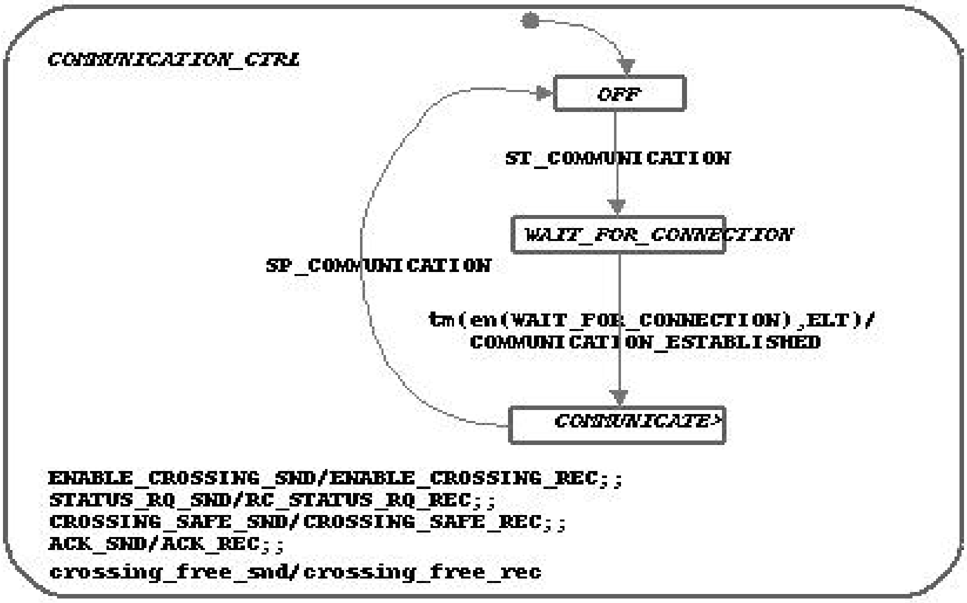

COMMUNICATION_CTRL
OFF
ST_COMMUNICATION
WAIT_FOR_CONNECTION
SP_COMMUNICATION
tm(en(WAIT_FOR_CONNECTION),ELT)/
COMMUNICATION_ESTABLISHED
COMMUNICATE>
ENABLE_CROSSING_SND/ENABLE_CROSSING_REC;;
STATUS_RQ_SND/RC_STATUS_RQ_REC;;
CROSSING_SAFE_SND/CROSSING_SAFE_REC;;
ACK_SND/ACK_REC;;
crossing_free_snd/crossing_free_rec

Figure 2: Statechart COMMUNICATION_CTRL

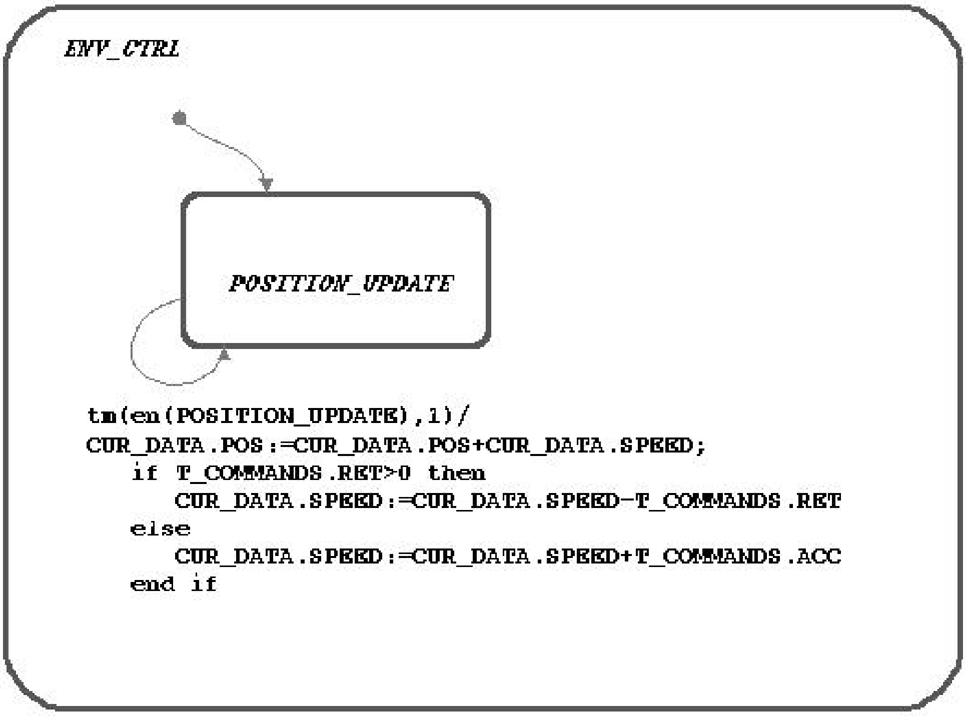
In the case that the crossing could not secure itself, CROSSING simply ignores the status request (STATUS_RQ), i.e. an explicit error message is not transmitted!

If the communication between TRAIN and CROSSING is to be terminated, then this is also done by the train via SP_COMMUNICATION which leads to an immediate abortion of the communication. This is modeled by changing into the state OFF in the COMMUNICATION_CTRL.

3 Environment

The behavior of the ENVIRONMENT is given by state chart ENV_CTRL (Fig. 3) which keeps track of the train's position (CUR_DATA.POS) and speed (CUR_DATA.SPEED) in the real world. Both values are updated in every super-step. This is realized by the expression tm(en(POSITION_UPDATE),1) which is true one super-step after the state POSITION_UPDATE is entered, i.e. the transition is taken every super-step. This timeout construct is widely used throughout the rest of the model. The new position is calculated by adding the train's current speed to the last position. The new speed is computed by adding the train's current acceleration, resp. subtracting its current retardation value, depending on which field of T_COMMANDS is set. If both fields are set to non-zero values at the same time, the retardation value has a higher priority. Generally, only one field should contain a non-zero value. The algorithm is based on measuring the distance in meters and the speed in meters per second for simplicity's sake. Other measurement units and/or algorithms can be substituted in more sophisticated versions of the model.

The reason to model this part of the environment is that there has to be a reference point for the train's dynamic data, i.e. here the 'true' position and speed of the train are calculated. Since the train computes these values as well, this allows us to also consider error situations where the data calculated by the train differs from the 'real' value calculated by the environment. The position provided by the ENVIRONMENT serves also as an input for the train sensor (see Sect. 5).



```
tm(en(POSITION_UPDATE),1)/
CUR_DATA.POS:=CUR_DATA.POS+CUR_DATA.SPEED;
   if T_COMMANDS.RET>0 then
      CUR_DATA.SPEED:=CUR_DATA.SPEED-T_COMMANDS.RET
   else
      CUR_DATA.SPEED:=CUR_DATA.SPEED+T_COMMANDS.ACC
   end if
```

Figure 3: State chart ENV_CTRL

4 Train

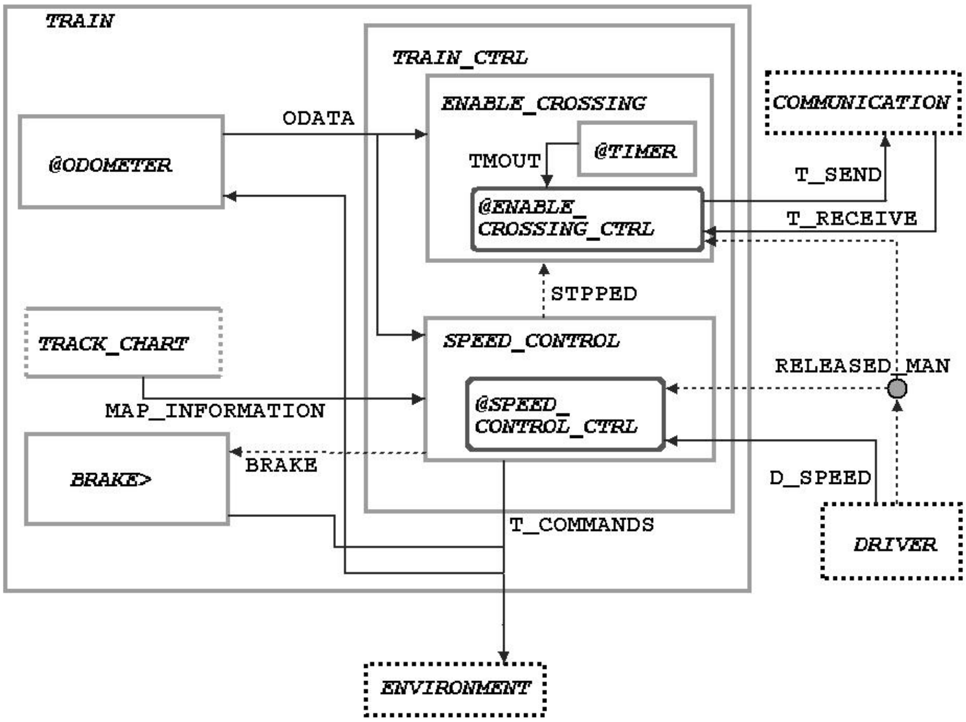


Figure 4: Activity chart TRAIN

The train consists of several sub-components, see figure 4. The activity TRAIN_CTRL forms the core of the train comprising the two functions of communicating with the crossings (ENABLE_CROSSING) and controlling the train's speed (SPEED_CONTROL). The ODOMETER computes the train's speed and position and the BRAKE is activated by the SPEED_CONTROL if the train is going too fast. The TRACK_CHART is an empty data store for the moment, but it will hold and provide the static track information in the future.

4.1 Speed Control

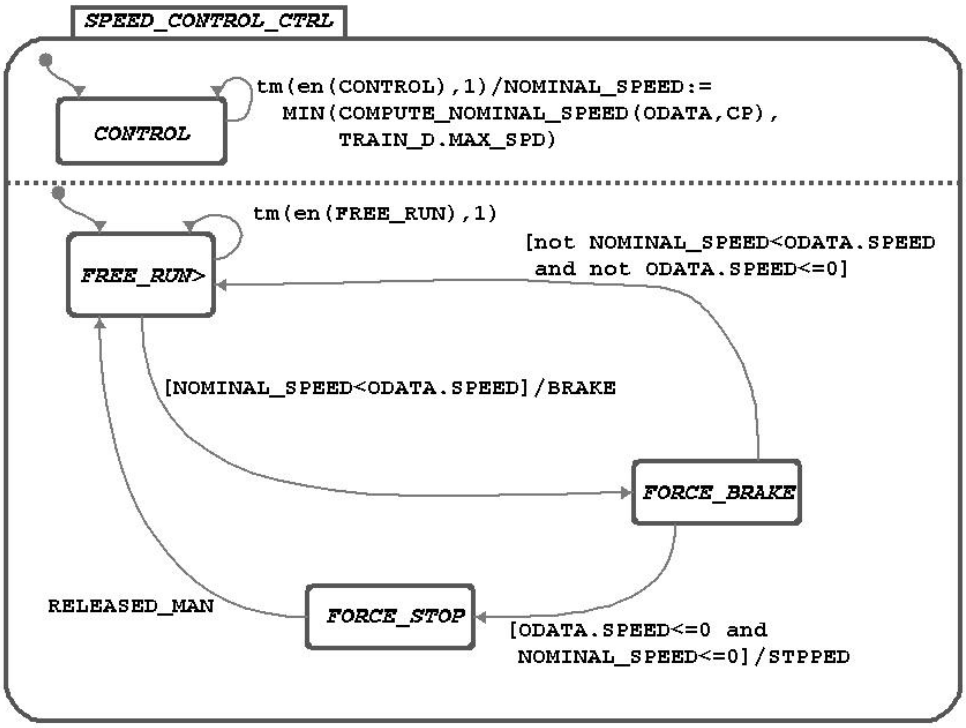


Figure 5: State chart SPEED_CONTROL_CTRL

The state chart SPEED_CONTROL_CTRL shown in figure 5 consists of two parallel substates; the upper one computes the maximally allowed speed (NOMINAL_SPEED), whereas the lower one checks if the train speed is below the maximum.

The computation of the NOMINAL_SPEED is done every super-step utilizing the timeout construct described in section 3. The actual computation is deferred to the function COMPUTE_NOMINAL_SPEED which takes the dynamic train data (ODATA) and the next control point (CP) as parameters. A control point is located in front of every crossing and represents a not secured crossing.[3] Control points may not be passed by a train unless the crossing is secured, i.e. the target speed at a control point is zero until the crossing is secured. A control point may be set, i.e. the target speed at its position is set to zero, or deleted, i.e. the target speed at its position is set to the maximal value for this track segment. All control points in a track segment are set when the segment is assigned to a train.

[3] A control point in general represents some sort of hazard. This can be a not secured crossing but also a switch in an unknown position, the end of track segment assigned to the train or a number of other possibly dangerous situations. Here we only consider control points induced by not secured crossings.

The function COMPUTE_NOMINAL_SPEED — as all other functions and procedures — is left unspecified here to allow different implementations suiting each user's needs and preferences. The resulting speed is the maximal speed for the current position and should take into account the train's own position, its distance to the next crossing, the status of the crossing and track-specific data provided by the track chart. Taking the minimum of the computed value and the train's maximal speed yields the overall maximal speed.

The lower substate checks if the actual train speed (ODATA.SPEED) is within the allowed range. If this is the case, we stay in state FREE_RUN and compute the new acceleration and retardation values depending on the speed requested by the driver (D_SPEED). A simple algorithm is shown here (The record T_COMMANDS contains the current acceleration and deceleration for the train and is also sent to the ENVIRONMENT):

```
en(FREE_RUN)/if (D_SPEED-ODATA.SPEED)<0 then
  T_COMMANDS.ACC:=0;
  T_COMMANDS.RET:=MIN(D_SPEED-ODATA.SPEED,TRAIN_D.MAX_RET)
 else
  T_COMMANDS.ACC:=MIN(D_SPEED-ODATA.SPEED,TRAIN_D.MAX_ACC);
  T_COMMANDS.RET:=0;
end if
```

If the driver's speed is greater than the train's actual speed, the train is accelerated, otherwise it is decelerated. If the two speeds are equal, the train is neither accelerated nor retarded. Again, this is only a simple example of an algorithm which distinguishes only two acceleration/deceleration degrees: none and maximum. More realistic algorithms can be used in more advanced versions of the model.

When the train speed is greater than the allowed speed, state FREE_RUN is exited, FORCE_BRAKE is entered and the brake is activated. Once the train speed is less than the maximal speed again we return to FREE_RUN and resume the above algorithm. If the NOMINAL_SPEED and the actual train speed are both zero[4], the train has stopped, state FORCE_STOP is entered and SPEED_CONTROL_CTRL emits the event STPPED to ENABLE_CROSSING_CTRL. Note the not every halting of the train is indicated by a corresponding STPPED. Only those stops are considered which result from the NOMINAL_SPEED dropping to zero. If the train stops for other reasons, it may resume its course on its own without intervention by the driver. But in the former case the driver has to confirm manually that the crossing may be passed safely (RELEASE_MAN) in order to continue. SPEED_CONTROL_CTRL then switches back into the normal behavior of state FREE_RUN.

4.2 Crossing Activation

The activity ENABLE_CROSSING (cf. Fig. 4) contains the state chart ENABLE_CROSSING_CTRL shown in figure 6, which handles the communication between train and crossing, and a timer (see Sect. 4.2.1) which is used to supervise that the train reaches a secured crossing in time. Here we first consider the communication behavior of the train described by ENABLE_CROSSING_CTRL. Once the train reaches the activation point — indicated by the condition V_ENABLE_POINT_P[5] — it changes its

[4] Because the braking procedure does not check, if the resulting speed is less than zero when subtracting the retardation value from the current speed, negative speeds can occur. Therefore it is necessary to use $\leq$ in the condition expression.

[5] Note that the conditions marked by the suffix _P represent procedures; in the current version they are modelled as conditions for simplicity's sake. Thus each user may implement the functionality which is abstracted from by these conditions in his preferred method. The condition V_ENABLE_POINT_P abstracts from the computation of the activation point for a crossing.

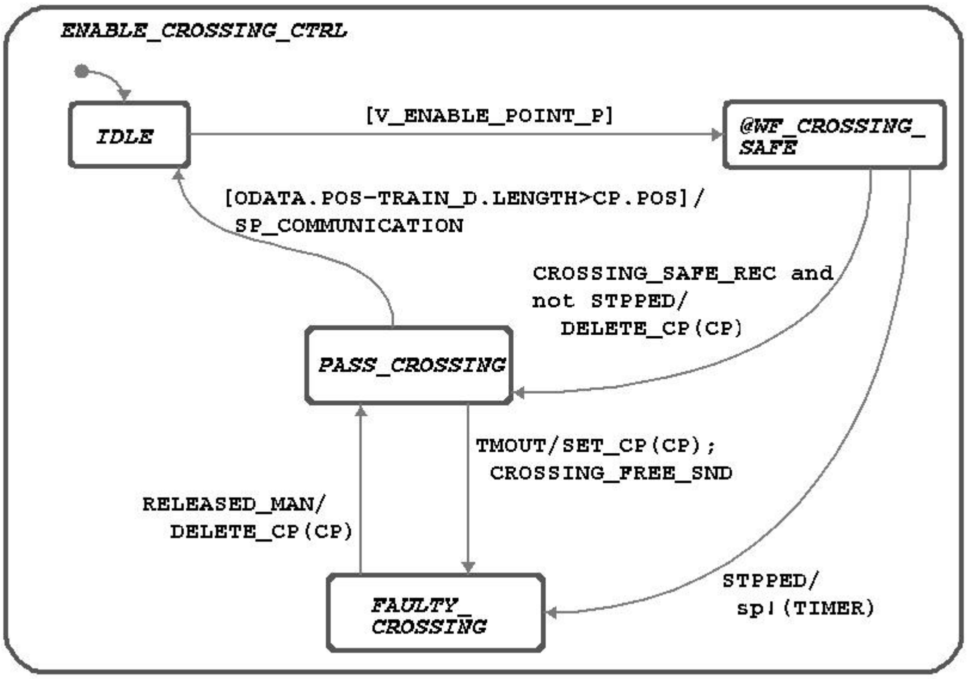


Figure 6: State chart ENABLE_CROSSING_CTRL

state from IDLE to WF_CROSSING_SAFE which realizes the protocol between the train and the communication channel. The detailed behavior is shown in state chart WF_CROSSING_SAFE in figure 7.

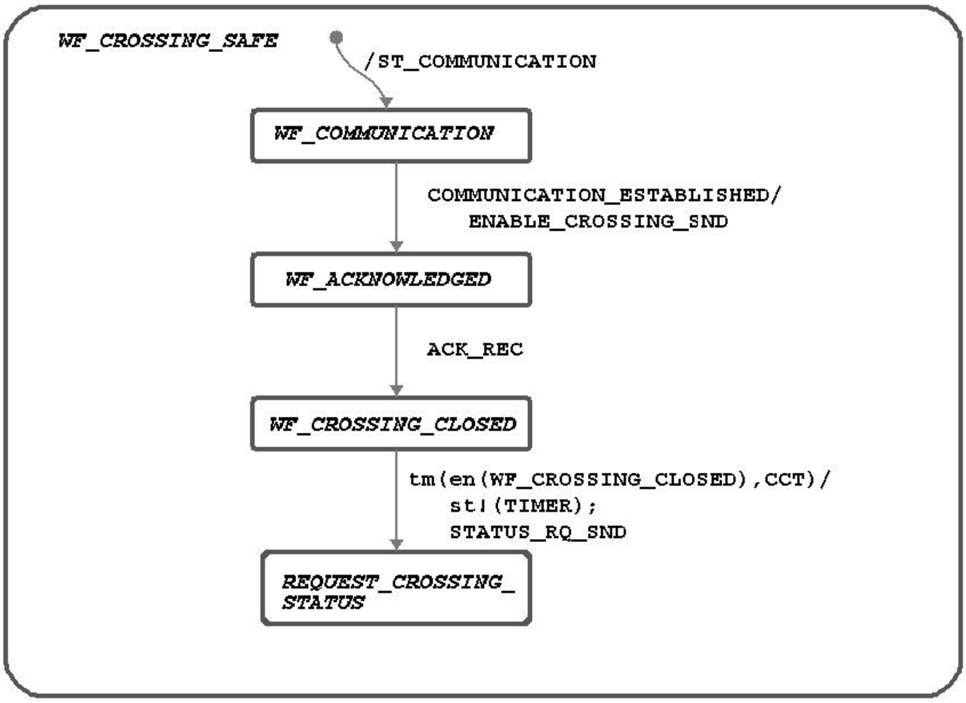


Figure 7: State chart WF_CROSSING_SAFE

On entering WF_CROSSING_SAFE the communication is started. Once the connection has been established, the train requests the securing of the crossing by emitting the event ENABLE_CROSSING_SND. On receiving the acknowledgment from the crossing, the train sends the status request after waiting an amount of time which corresponds to the time needed for the crossing to carry out the securing procedure. This is the crossing closing time CCT. Simultaneously with the status request a timer is started which supervises that the train reaches the crossing in time (see Sect. 4.2.1). In the last state of WF_CROSSING_SAFE the status message of the crossing is awaited.

Returning to ENABLE_CROSSING_CTRL, we first consider the normal case, i.e. the crossing reports itself safe. Thus the train is still moving, the status message CROSSING_SAFE_REC arrives, the state PASS_CROSSING is entered and the control point is deleted by the function DELETE_CP.[6] Note that the functions executing the deleting and setting of control points are left unspecified (see above). When the train now passes the crossing – represented by its control point – the communication channel is closed and the train is ready for the next crossing. For the computation when the train has passed the crossing the train length has to be taken into account in order to avoid that the train dismisses the crossing while having passed it only partially.

During the communication two error situations can arise: First, the crossing may not be able to secure itself. In this case it does not answer the status request and therefore the train cannot delete the control point with the result that it stops in front of the crossing. This is indicated by SPEED_CONTROL_CTRL with the event STPPED triggering the transition from WF_CROSSING_SAFE to FAULTY_CROSSING. Since the train has stopped already, it will not reach the crossing in time and therefore the timer is stopped. In this situation the driver has to manually confirm that the crossing can be safely passed (RELEASE_MAN) entering state PASS_CROSSING and deleting the control point in order to allow the train to pass it.

The second error situation arises when the crossing has answered the status request but the train is unable to pass it within the maximal barrier shut time. This is indicated by the event TMOUT sent by the timer resulting in changing from state PASS_CROSSING to FAULTY_CRCOSSING, setting the control point again via the function SET_CP and notifying the crossing that the train will not reach it in time (event CROSSING_FREE_SND). Again this situation has to be resolved by the driver.

4.2.1 Time Supervision

The timer shown in figure 8 supervises that the train reaches an already secured crossing before the maximal barrier closed time elapses, i.e. the maximum amount of time that a crossing may stay closed without a train passing it. It generates a timeout when this property is violated.

The timer implements a simple counter which increments a counter variable T. The timeout (TMOUT) is generated depending on two conditions, V_STILL_SAFE_P and V_BRAKE_POINT_P, which again represent procedures (or rather the result of procedures):

V_STILL_SAFE_P indicates, if the train will pass an already *secured* crossing within the maximum barrier closed time. The computation of the value of this condition should take the current train speed and position into account.

V_BRAKE_POINT_P indicates, if the train has reached the braking point, i.e. the point where it would have to start braking in order to safely stop in front of the crossing. This computation again depends on the current train speed and position.

[6] Recall that all control points are assumed to have been set initially.

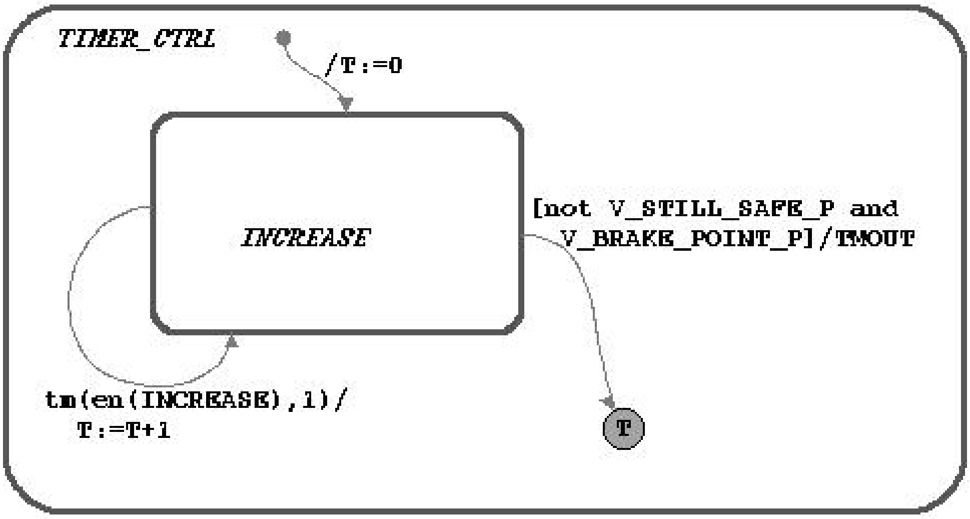
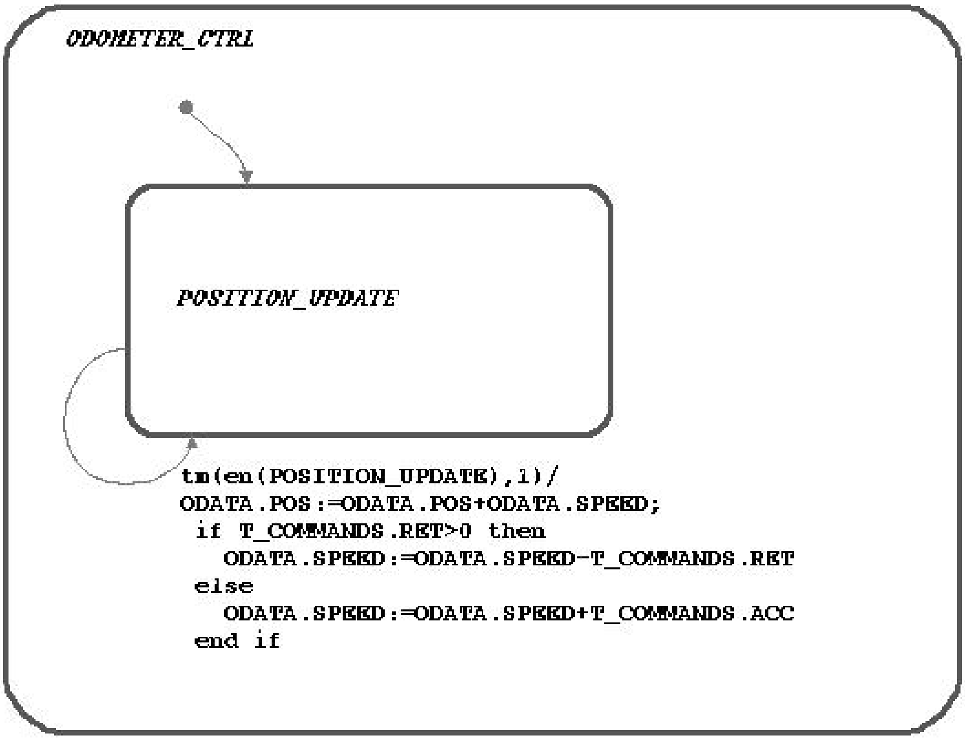


Figure 8: State chart TIMER_CTRL

The behavior suggested by the transition to the termination connector in figure 8 is thus: If the train reaches its braking point according to the current speed and is unable to reach the crossing before the maximum barrier closed time elapses, the timeout is generated and the timer is stopped. The timeout event is sent to ENABLE_CROSSING_CTRL.

4.3 Odometer



```
tm(en(POSITION_UPDATE),1)/
ODATA.POS:=ODATA.POS+ODATA.SPEED;
 if T_COMMANDS.RET>0 then
   ODATA.SPEED:=ODATA.SPEED-T_COMMANDS.RET
 else
   ODATA.SPEED:=ODATA.SPEED+T_COMMANDS.ACC
 end if
```

Figure 9: State chart ODOMETER_CTRL

The ODOMETER (Fig. 9) is responsible for the computation of the actual speed and position of the train. In the present version the algorithm is the same as the one used in the ENVIRONMENT; see section 3 for a detailed description. Future extensions of the model can use different algorithms for the ENVIRONMENT and the ODOMETER to model erroneous speed and position calculations of the train.

4.4 Brake

The BRAKE uses a very simple scheme: when activated it brakes with full force, i.e. the respective fields of T_COMMANDS are set to the maximum deceleration value of the train and to zero. This is realized by the mini spec:

```
BRAKE/
   T_COMMANDS.ACC:=0;
   T_COMMANDS.RET:=TRAIN_D.MAX_RET
```

5 Crossing

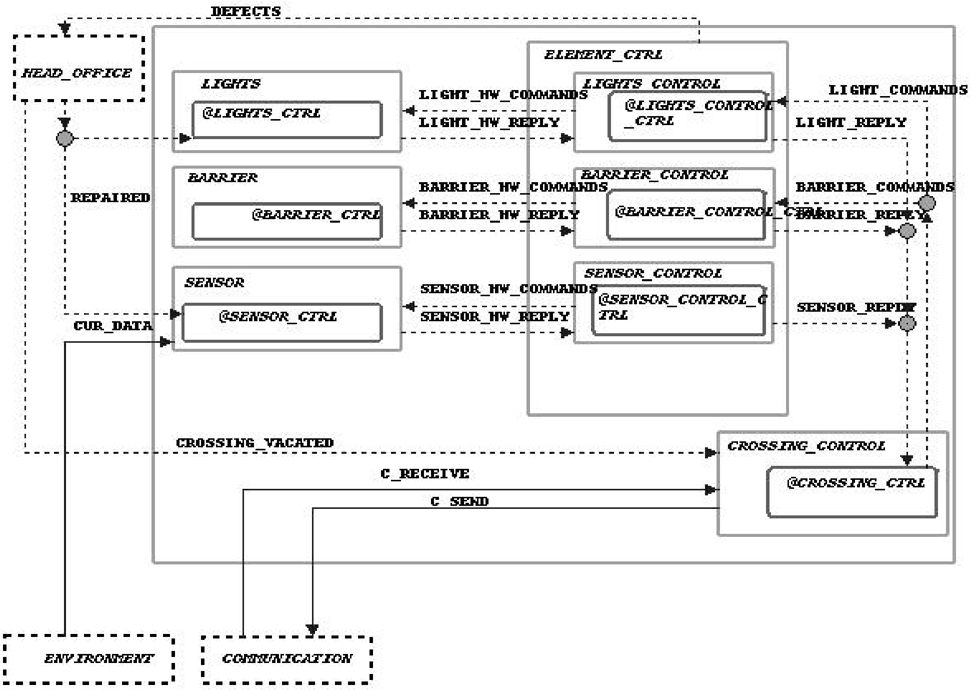


Figure 10: Activity-Chart CROSSING

The activity CROSSING (see Fig. 10) contains the overall software control of the crossing (CROSSING_CTRL) which is responsible for the coordination of the whole securing process, the component software control (CROSSING_CTRL) for the involved hardware consisting of the LIGHTS_CONTROL, the BARRIER_CONTROL, and the SENSOR_CONTROL, as well as for each component separately an activity for the description of the hardware functionality, which are the activities LIGHTS, BARRIER, and SENSOR.

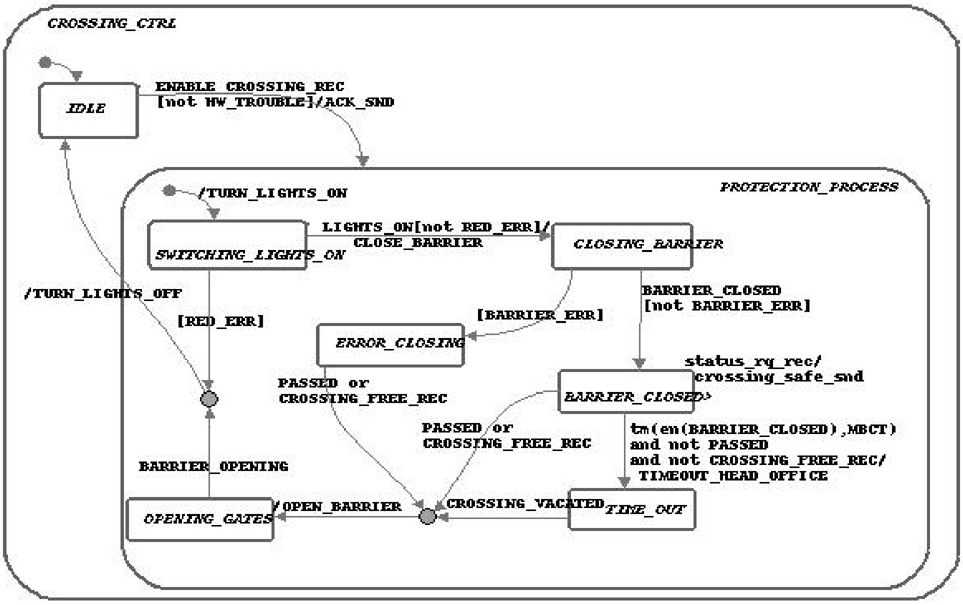


Figure 11: Statechart CROSSING_CTRL

5.1 Overall Software Control (CROSSING_CONTROL)

The function of this component is the coordination of all measures while closing or opening the crossing. This includes the control of the 'normal' securing process (traffic lights on, barrier down, barrier up, lights off), and the consideration of further secondary constraints, for example the maximum time limit for the secure status, as well as error handling.

The initial state IDLE remains activated until the control receives the signal ENABLE_CROSSING_REC; thereupon if the system is not in an error condition (i.e. HW_TROUBLE = $false$) then the state PROTECTION_PROCESS will be entered which encapsulates all further states. A hardware error is present if at least one of the components red light, barrier or sensor operates incorrectly (the condition HW_TROUBLE = RED_ERR $\vee$ BARRIER_ERR $\vee$ SENSOR_ERR is defined in CROSSING_CTRL).

As mentioned above, the securing process itself consists of the handling of the traffic lights and the barriers.

Upon entering the PROTECTION_PROCESS the state SWITCHING_LIGHTS_ON is activated and the event TURN_LIGHTS_ON is sent to LIGHTS_CONTROL, where it initiates the signal sequence YELLOW → RED. The control remains in this state until either receiving the event LIGHTS_ON or a red light malfunction is detected (RED_ERR), with both events originating in the activity LIGHTS_CONTROL.

Error Handling: If during the activation of the traffic light the red light fails, then the rest of the protection process is aborted, the request TURN_LIGHTS_OFF is sent to the traffic light control (thus the traffic light device is deactivated) and the initial state IDLE is entered. This procedure implies that no CROSSING_SAFE message is replied to the approaching train and the crossing is regarded as 'unsafe'. Also for repeated securing requests the sequence of events is correct, since with a red light defect a hardware error is present (HW_TROUBLE = $true$) and thus the signal ENABLE_CROSSING_REC is ignored.

Furthermore no explicit resetting of the overall software control is needed when the damage of the traffic lights device is repaired because being in the IDLE state normal operation can take place once the lights are repaired.

After the crossing has been successfully secured by the traffic lights the signal CLOSE_BARRIER will be sent to the BARRIER_CONTROL. The system remains in the state CLOSING_BARRIER until either the barrier closing process is completed (indicated by BARRIER_CLOSED) or a barrier hardware error is reported (BARRIER_ERR).

Under normal conditions the control stays in the state BARRIER_CLOSED until the train has passed (indicated by the signal PASSED of the SENSOR or the message CROSSING_FREE of the TRAIN) or the 'maximum barrier closed time' (MBCT) has expired. If a status message is requested by means of STATUS_RQ the crossing responds with CROSSING_SAFE.

Error Handling (ERROR_CLOSING, TIME_OUT):

1. On the other hand if there is some failure (BARRIER_ERR) during the closing of the barrier (i.e. control in state CLOSING_BARRIER) which will be reported by the BARRIER_CONTROL the state ERROR_CLOSING will be entered without aborting the overall process. The release of the status message will be suppressed so the crossing remains 'unsafe'. The error state will only be left when the train has passed whereupon the normal process will be continued by opening the crossing.

   If the barrier opens correctly the failure indicator BARRIER_ERR will be reset by BARRIER_CONTROL and if no further hardware defects are present the crossing will be considered operational.

   The traffic lights are turned off in any case and the CROSSING_CONTROL enters the state IDLE. The further functional behavior depends on the flag HW_TROUBLE.

2. Another exception is necessary for the case that the allowed limit MBCT for the crossing to stay in the 'safe' state is exceeded (TIME_OUT). This is no device failure of the crossing but nevertheless an error message (TIMEOUT_HEAD_OFFICE) will be sent to the HEAD_OFFICE to inform about this special situation. The crossing remains 'safe' until the explicit signal CROSSING_VACATED is received from the head office. At that moment the normal event-sequence will be continued just as if the train had passed properly.

After the CROSSING_CONTROL has detected the passing of the train (PASSED, CROSSING_FREE_REC or CROSSING_VACATED) an opening request (OPEN_BARRIER) will be sent to BARRIER_CONTROL while the CROSSING_CONTROL stays in the state OPENING_GATES. This is indicated by the BARRIER_OPENING signal which will be given as soon as the barrier has left the lower position.

Thereupon the lights will be turned off by means of TURN_LIGHTS_OFF and the CROSSING_CONTROL returns to IDLE.

Error Handling: There is no explicit error handling during the opening process. The implicit behavior in case of a failure is that with fully closed barriers the traffic lights remain turned on (=RED) whereas the lights are turned off when the barriers are not correctly closed any more, i.e. even if the barriers don't reach their upper position (OPENED) the crossing will be opened to traffic. This behavior holds back the traffic no longer than necessary in case of a technical failure.

5.2 Traffic Lights

The whole traffic lights device contains – as mentioned above – the software (LIGHTS_CONTROL, see Fig. 12) as well as the hardware part (LIGHTS, see Fig. 13).

Between the two components there are information flows in each direction (see Appendix B.2). These contain commands from the software to the hardware

(LIGHTS_HW_COMMANDS) which are the light control and test request, and in opposite the reply (LIGHT_HW_REPLY) with the test results.

Additionally there is an information exchange between LIGHTS_CONTROL and the CROSSING_CONTROL for the overall light commands (LIGHT_COMMANDS) to turn on/off the lights as well as status messages (LIGHT_REPLY) about command completion and errors.

Furthermore the LIGHTS_CONTROL sends information about hardware defects (as part of DEFECTS) to the HEAD_OFFICE which emits the REPAIRED signal to the LIGHTS hardware.

5.2.1 Traffic Lights Software (LIGHTS_CONTROL)

The software control is responsible for the control of the hardware device. Its behavior is defined as follows:

1. It is to be guaranteed that the crossing is open to traffic at least for the 'minimum green time' (MGT) before closing it again after it has been opened, i.e. each phase of lights turned off has to be MGT time units or longer.

2. After activation of the device the yellow light is turned on for the 'minimum yellow time' (MYT). In case the yellow light is faulty or fails during the yellow phase the remaining amount of MYT is added to the leadtime of the red light.

3. Prior to sending the status LIGHTS_ON to the CROSSING_CONTROL the red light has to be turned on for at least 'minimum red time closing' (MRTC) time units (i.e. the leadtime of the red light).

4. When the signal TURN_LIGHTS_OFF has been received or in case of a failure of the red light the traffic lights are turned off without any delay and the timer which counts the duration of the turned-off phase – 'green time' (GT) – starts.

As shown in Fig. 12 the software model is built of two main states: the state OFF to model the traffic lights being turned off, and the state ON which encapsulates all active processes. The following items describe the way our model realizes the above specification:

Entering OFF the SWITCH_OFF signal is sent to the hardware to ensure that all lights are turned off and to start the GT counter. This timer will be increased each step.

Depending on the GT counter the reaction to the command TURN_LIGHTS_ON differs: If the GT counter has not yet reached the MGT the system branches to PENDING where GT is increased further on.

However, when at last GT has reached the MGT the command SWITCH_ON is sent to the hardware to activate the yellow light and the state YELLOW is entered. This starts the counter 'elapsed yellow time' (EYT). EYT measures the period of time the yellow light is on.

Sending the command SWITCH_OVER which causes the lights to switch from yellow to red the state RED is entered. This will be done when EYT has reached MYT or if the yellow light fails. As mentioned above the signal LIGHTS_ON will only be sent when the remaining yellow time ($=$ MYT $-$ EYT) and the red light leadtime (MRTC) have passed.

As soon as the command TURN_LIGHTS_OFF has been received or a failure of the red light has been detected (RED_ERR) the light control switches back to OFF and the traffic lights device is turned off.

The traffic light software control contains in addition to the software control of the sensor (see 5.4.1) a parallel process for the purpose of cyclic self diagnosis.

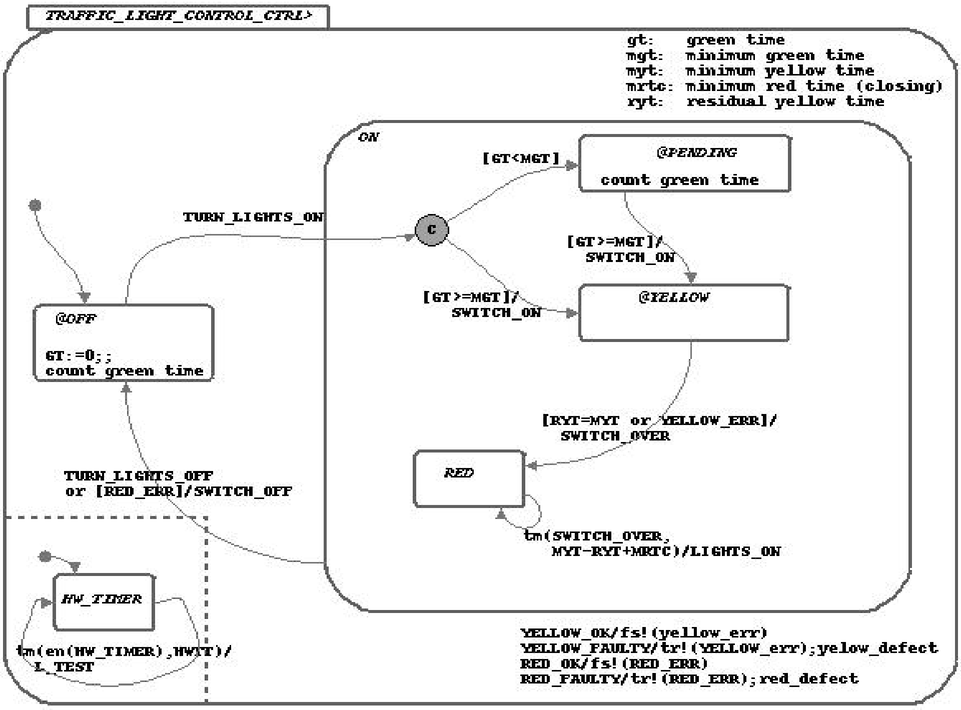


Figure 12: Statechart LIGHTS_CONTROL_CTRL

It consists of only a single state (HW_TIMER) with a loop executed infinitely with a delay defined by the 'hardware test time' (HWTT). When the loop is executed the hardware is asked by means of L_TEST to check its functionality.

Depending on the response in LIGHT_HW_REPLY the variables YELLOW_ERR and RED_ERR are set and if necessary the HEAD_OFFICE is informed via the error messages YELLOW_DEFECT and/or RED_DEFECT. This is done by the static reactions defined in LIGHTS_CONTROL_CTRL (see Fig. 12).

5.2.2 Traffic Lights Hardware (LIGHTS)

The model of the traffic lights hardware describes the behavior of the traffic lights in the real world. As for our purposes only the functional aspects of the devices are of interest physical details are left aside.

The statechart LIGHTS_CTRL consists of states to indicate which light is on (see Fig. 13). Changing from one state to another is controlled by the commands received from the software control (see Sect. 5.2.1). Initially all lights are off (OFF).

Analogously to the software test cycle described above, which is identical in all software controls (except for the barrier software), all hardware statecharts have in common the existence of parallel processes to simulate hardware failures. Because we are only interested in whether a component works or not, the parts of the statecharts simulating failures all look the same:

Starting with an initial state (xxx_OK[7]) indicating no hardware problems, in each step an error of the device may occure. This is modeled through an indeterministic choice of the transition out of the xxx_OK state. Either the state in the next step is xxx_OK or xxx_FAULTY, which represents the error state. The replies to the software control in case of the hardware test xxx_TEST are depending on these two states.

[7] 'xxx' standing for the hardware device in discussion

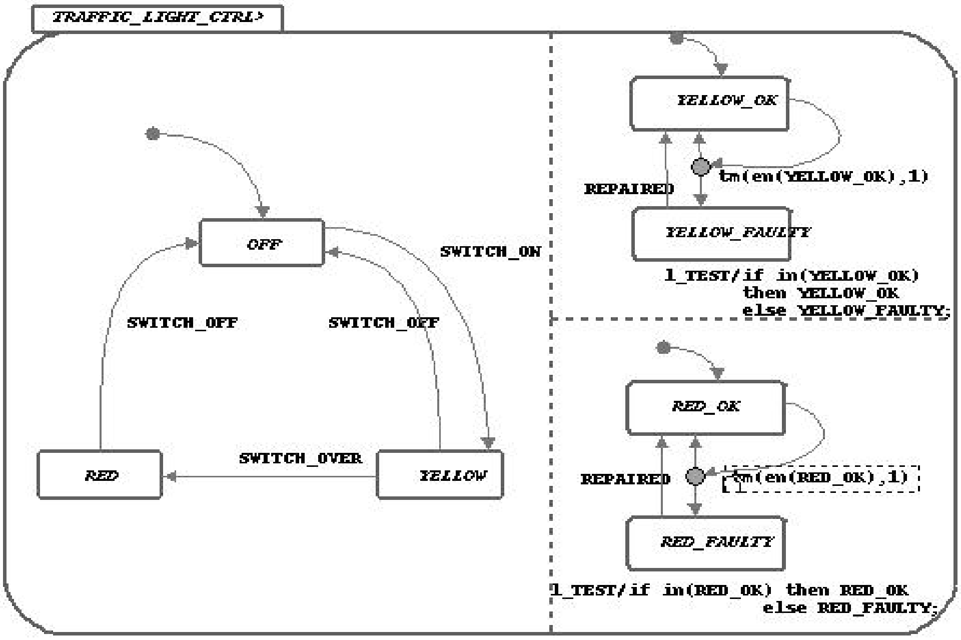


Figure 13: Statechart LIGHTS_CTRL

Except for the barrier, the error state is only left when the REPAIRED signal from the HEAD_OFFICE is received. The REPAIRED signal is sent to all hardware devices.

Since there are two independent parts of the traffic lights which can fail – the red and the yellow light – each of them is modeled separately. The initial states are labeled YELLOW_OK and RED_OK respectively, the error states are YELLOW_FAULTY and RED_FAULTY, and a test report is requested by the L_TEST command.

5.3 Barriers

As the other components of the crossing the barriers consist of a software control (BARRIER_CONTROL, see Fig. 14) containing the logic and the hardware (BARRIER, see Fig. 15) simulating the physical aspects.

The closing and opening of the barriers is controlled by the barrier software module BARRIER_CONTROL which receives the appropriate commands (CLOSE_BARRIER, OPEN_BARRIER) from the overall software control (see Sect. 5.1) and translates them into action by commands (LOWER, RAISE) to the hardware device BARRIER. The software replies to the CROSSING_CONTROL by means of BARRIER_CLOSED, BARRIER_OPENING, and the failure report BARRIER_ERR, while itself getting responses from the hardware (CLOSED, OPENED). If errors occur these are signaled to the HEAD_OFFICE by the software control via BARRIERS_DEFECT.

5.3.1 Barrier Software (BARRIER_CONTROL)

The behavior of the barrier software control (see Fig. 14) has been modeled corresponding to the following description (for an overview of the control and information flows see Appendix B.3):

1. The crossing is closed and opened on request of the overall software control (CROSSING_CONTROL) without delay by lowering and raising the barriers. Further commands given during one of these phases (CLOSING, OPENING) are ignored. Only error exceptions are handled.

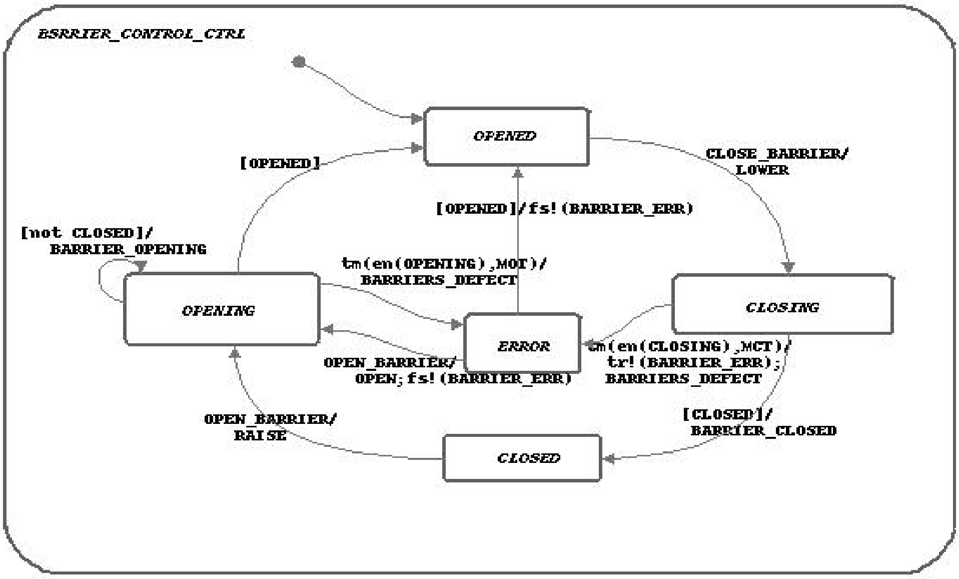


Figure 14: Statechart BARRIER_CONTROL_CTRL

2. The barrier device informs the CROSSING_CONTROL of the successful closing of the barriers by means of BARRIER_CLOSED (initiated by the condition CLOSED being set to *true* by the hardware) and of the beginning of the opening by means of BARRIER_OPENING (initiated by the condition CLOSED being set to *false*). There is no explicit message to CROSSING_CONTROL about having opened the barriers successfully.

3. There are maximum time limits for the closing ('maximum closing time' (MCT)) as well as the opening process ('maximum opening time' (MOT)). If the execution time for at least one of the operating phases exceeds its limit a hardware failure is assumed.

   Because the barriers are mechanical devices without any electrical equipment to control the functionality this kind of error detection is necessary. Whether the mechanics works correctly can only be determined in action. So the software control of the barriers contains no cyclic self diagnosis routines.

4. If a failure has been detected (i.e. the state ERROR has been activated), then the normal processing can only be continued when the barriers are fully opened (switch to the state OPENED) or the OPEN_BARRIER command is received. Each try to open the barriers again has to preserve the MOT limit.

   Leaving the ERROR state the error flag BARRIER_ERR is reset so that the barrier device is again available for the further operation. However because each entering of ERROR causes a message (BARRIERS_DEFECT) being sent to the HEAD_OFFICE, the staff is informed about each failure even if the mechanics works well in the meantime.

5.3.2 Barrier Hardware (BARRIER)

Because when describing the physical behavior of barriers time is relevant the model of the barrier hardware (BARRIER_CTRL) is not as simple as providing states for 'up' and 'down', even though these two states (OPEN and CLOSE) also exist in our model, of course. The additional states CLOSING and OPENING model the temporal aspects (see Fig. 15).

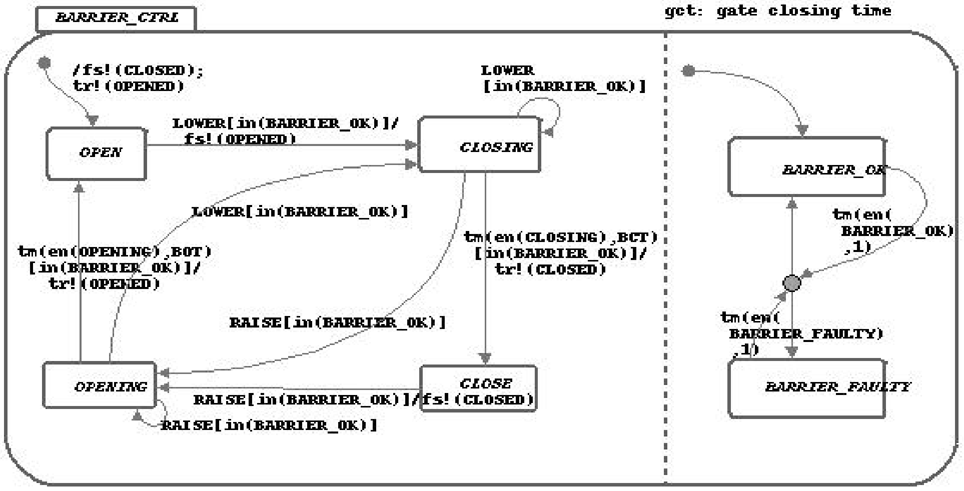


Figure 15: Statechart BARRIER_CTRL

Initially the conditions CLOSED and OPENED are initialized (CLOSED := $false$, OPENED := $true$). The further operation is as follows:

1. Receiving the LOWER command in the OPEN state with no hardware failure present the model switches to the CLOSING state setting OPENED to $false$. This means the barriers are no longer open but have not yet been closed.

2. After the 'barrier closing time' (BCT) has passed and the device is still 'operational' the CLOSE state is reached. The condition CLOSED is set to $true$; the barriers are closed.

   If instead a hardware failure recurs (i.e. the state BARRIER_FAULTY of the failure simulation is active) the CLOSING state remains active even if the BCT has passed. So the condition CLOSED is not changed.

   The third possibility while closing the barriers, is that the RAISE command is received. During normal operation this can never happen according to the model of the barrier software control (see 5.3.1). But if the hardware fails during the closing operation this is the way to get back to an operational state.

   Furthermore while beeing in the CLOSING state a LOWER command can occure. This may be when after a first LOWER comand a barrier device failure occurs and the barriers are not closed. Then the devices stays in the state CLOSING and when a second LOWER command occurs the barrier may in the meantime be operational and a 'closing' cycle should be possible. Therefore the transition from CLOSING to CLOSING resets the 'barrier closing time'.

3. With the barriers closed successfully and operational the command RAISE initiates the opening phase. The variable CLOSED being reset to $false$ indicates that the barriers are no longer closed.

   Similar to the lowering process also when raising the barriers the OPENING state stays active until – normally after a delay determined by the 'barrier opening time' (BOT) – the barriers have reached the upper position. With this step the condition OPENED is set to $true$ and the OPEN state is entered.

In the real world the upper and lower position of a barrier have sensors to signal contact with the gate. This model does without them.

As far as the simulation of failures is concerned it is the same with the BARRIER_CTRL as with the other hardware devices (see the paragraph about the hardware failure simulation, page 15) with the difference that there is no REPAIRED signal from the HEAD_OFFICE to leave the faulty state. Instead the BARRIER_FAULTY state behaves as the BARRIER_OK state with also a functionality decision each step depending on BARRIER_OUT_OF_ORDER.

5.4 Sensor

A sensor in the context of a level crossing is a piece of equipment installed at the railroad tracks to detect passing trains. This reference model only provides a simple view of a sensor which detects a train when it is located above the sensor.

The communication between the software (SENSOR_CONTROL) which implements the logic of the sensor and the hardware (SENSOR) contains on one side the raw information whether the hardware detects a train (SENSOR_ON) and on the other side the request for a status message (S_TEST) and its answer (SENSOR_OK, SENSOR_FAULTY) respectively.

The software control of the sensor emits the PASSED signal indicating that a train has passed to the CROSSING_CONTROL as well as an error message (SENSOR_ERR) if necessary. The latter message is also sent to the HEAD_OFFICE by means of SENSOR_DEFECT. As to the traffic lights hardware the REPAIRED signal is also sent to the sensor hardware SENSOR.

Unique to this device is the data transfer from the ENVIRONMENT activity to the SENSOR providing it with the information about the actual train position. This information is needed to determine whether the train is located above the sensor.

(A list of the flows connected to the sensor component can be found in the appendix B.4.)

5.4.1 Sensor Software (SENSOR_CONTROL)

The sensor software (see Fig. 16) works as follows: As soon as the hardware of the sensor is activated (condition SENSOR_ON) the initial state IDLE is left and instead the ACTIVATED state is entered. This is interpreted as the train starting to pass the sensor.

When the SENSOR_ON condition is reset to $false$ which means that the train has fully passed the corresponding signal PASSED is sent to the CROSSING_CONTROL and the software control changes back to the IDLE state.

Analogous to the traffic lights (see the paragraph about the software self diagnosis cycle, page 14) the sensor software control performs a cyclic self test requesting a status message of the hardware device by means of S_TEST. In case of a hardware failure the SENSOR_ERR condition used by the CROSSING_CONTROL is set and the SENSOR_DEFECT message is reported to the HEAD_OFFICE.

5.4.2 Sensor Hardware (SENSOR)

The structure of the sensor hardware model is quite simple but the details are more complicated as for the other hardware components. At a glance (see Fig. 17) the hardware control contains the two states OFF and ON as well as the parallel failure simulating process that is typical for all hardware units (see the paragraph about the hardware failure simulation, page 15).

But the decision when to switch from OFF to ON is not as easy as might be expected. In this model the behavior of the sensor is defined as follows:

- An operational sensor is activated as soon as the last position of the head of the train is located before the sensor position and the actual position

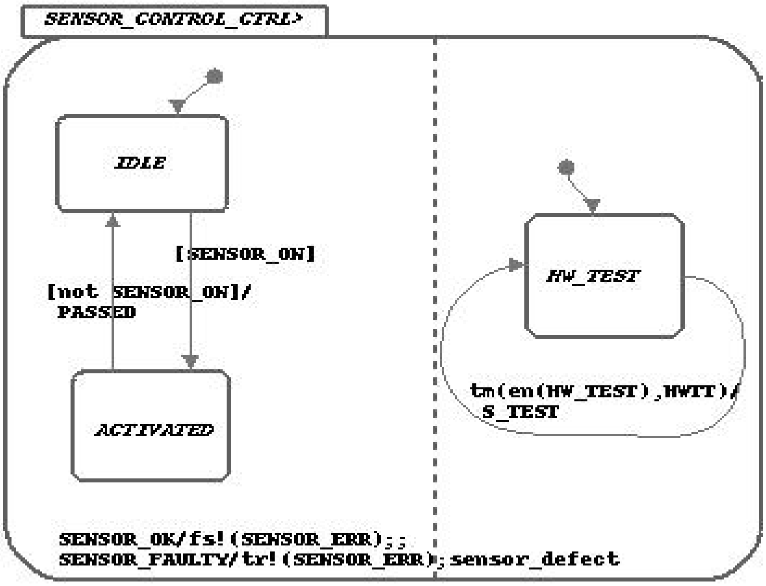


Figure 16: Statechart SENSOR_CONTROL_CTRL

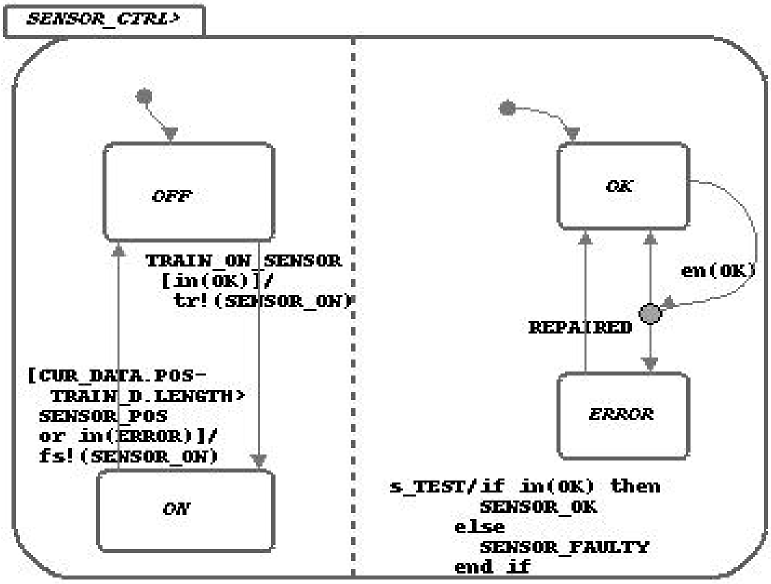


Figure 17: Statechart SENSOR_CTRL

behind or above it. For this purpose the variable LAST_POS is introduced which is updated each step with the last position of the train taken from CUR_DATA.POS. The event TRAIN_ON_SENSOR is raised if the above condition is true. This condition is checked in a separate parallel process with the single state TRAIN_PASSED.

The definition implicitly contains the fact that the sensor is only activated (ON) if the train passes in forward direction (i.e. in direction with greater position values).

- If there are no failures the sensor is deactivated (OFF) when the tail of the train, which is located at CUR_DATA.POS − TRAIN_D.LENGTH, has passed the sensor.

This implies that if a train starts passing the sensor in a forward direction, stops and at the end leaves the sensor backwards, then the sensor will stay activated infinitely.

- A faulty sensor always switches to the OFF state, i. e. no train will be detected.

  This can cause a PASSED signal being submitted to CROSSING_CONTROL by SENSOR_CONTROL even though a train may still be located above the sensor. The actual model does not take care of that possibility.

6 Acknowledgement

We would like to thank the projects KNOSSOS and SafeRail for the serious discussions on the radio-base crossing control case study. These discusions were necessary for the understanding of case study. Further we would thank Alexander Puschnig who helped us in modelling and documenting the case study.

A Data Types

Here follows a short description of the data types used for modelling the radio-based crossing control system.

- `NATS_T`
  The *natural numbers* are the types for almost all variables which represent numbers in the model.

- `DYN_DATA_T`
  This data type is a record for the dynamic train datas and contains the current position (`POS`) and speed (`SPEED`).

- `STATIC_DATA_T`
  The static train information stored in `STATIC_DATA_T`, also a record. This data type contains entries for the length of the train (`LENGTH`), the maximal retardation (`MAX_RET`), the maximal acceleration (`MAX_ACC`), the minimal speed (`MIN_SPD`, when the train drives backwards), and the maximl speed (`MAX_SPD`).

B Information Flows

Here is an enumeration of the most important control and information flows of our reference model. The arrow ('→') indicates the direction of data exchange.

B.1 Communication

For the control of the communication there are commands and responses between TRAIN and COMMUNICATION:

- TRAIN → COMMUNICATION
  - ST_COMMUNICATION
    initiates the communication between TRAIN and CROSSING by establishing a radio link
  - SP_COMMUNICATION
    aborts the communication between TRAIN and CROSSING
- COMMUNICATION → TRAIN
  - COMMUNICATION_ESTABLISHED
    status message 'Communication established'

Between the TRAIN and the CROSSING there are the following messages which are exchanged via the COMMUNICATION:

- TRAIN → CROSSING (in T_SEND/C_RECEIVE):
  - ENABLE_CROSSING_SND ↦ ENABLE_CROSSING_REC
    request to secure the crossing
  - STATUS_RQ_SND ↦ STATUS_RQ_REC
    request for status message
  - CROSSING_FREE_SND ↦ CROSSING_FREE_REC
    message about the vacation of the crossing
- CROSSING → TRAIN (in C_SEND/T_RECEIVE):
  - ACK_SND ↦ ACK_REC
    acknowledgement for closing request
  - CROSSING_SAFE_SND ↦ CROSSING_SAFE_REC
    status message 'Crossing safe'

As mentioned in Section 2 the transformation ('↦') of a sent message (_SND) to a received message (_REC) is done by the COMMUNICATION activity.

B.2 Traffic Lights

This section describes the command and information flows concerning the traffic lights. The functionality of the lights is controlled by the overall crossing control by means of these messages:

- CROSSING_CONTROL → LIGHTS_CONTROL (in LIGHT_COMMANDS):
  - TURN_LIGHTS_ON
    request to turn on the traffic lights by switching on the yellow light
  - TURN_LIGHTS_OFF
    request to turn off the traffic lights

- `LIGHTS_CONTROL` → `CROSSING_CONTROL` (in `LIGHT_REPLY`):
  - `LIGHTS_ON`
    indicates that the turn-on process is finished
  - `YELLOW_ERR`
    indicates a failure of the yellow light
  - `RED_ERR`
    indicates a failure of the red light

The hardware device is controlled by the commands of the `LIGHTS_CONTROL`:

- `LIGHTS_CONTROL` → `LIGHTS` (in `LIGHT_HW_COMMANDS`):
  - `SWITCH_ON`
    request to turn on the yellow light
  - `SWITCH_OVER`
    request to switch off the yellow and turn on the red light
  - `SWITCH_OFF`
    request to turn off all lights
  - `L_TEST`
    request for test report
- `LIGHTS` → `LIGHTS_CONTROL` (in `LIGHT_HW_REPLY`):
  - `RED_OK`
    test report 'Red light ok'
  - `RED_FAULTY`
    test report 'Red light faulty'
  - `YELLOW_OK`
    test report 'Yellow light ok'
  - `YELLOW_FAULTY`
    test report 'Yellow light faulty'

There is also some interaction with the `HEAD_OFFICE`:

- `LIGHTS_CONTROL` → `HEAD_OFFICE` (in `DEFECTS`):
  - `YELLOW_DEFECT`
    error message 'Yellow light faulty'
  - `RED_DEFECT`
    error message 'Red light faulty'
- `HEAD_OFFICE` → `LIGHTS`:
  - `REPAIRED`
    the fact that all hardware devices are repaired

B.3 Barriers

The control and information flows concerning the barriers are described in this section. Analogous to the lights (see Appendix B.2) the actions of the barriers are controlled by the overall crossing control:

- CROSSING_CONTROL → BARRIER_CONTROL (in BARRIER_COMMANDS):
  - CLOSE_BARRIER
    request to lower the barriers
  - OPEN_BARRIER
    request to raise the barriers
- BARRIER_CONTROL → CROSSING_CONTROL (in BARRIER_REPLY):
  - BARRIER_OPENING
    indicates that the opening process has started
  - BARRIER_CLOSED
    indicates that the barriers are closed
  - BARRIER_ERR
    indicates a failure of the barriers

The hardware device is controlled by the commands of the BARRIER_CONTROL:

- BARRIER_CONTROL → BARRIER (in BARRIER_HW_COMMANDS):
  - LOWER
    request to lower the barriers
  - RAISE
    request to raise the barriers
- BARRIER → BARRIER_CONTROL (in BARRIER_HW_REPLY):
  - CLOSED
    indicates that the barriers are closed
  - OPENED
    indicates that the barriers are opened

For the purpose of error notification there is some communication with the HEAD_OFFICE:

- BARRIER_CONTROL → HEAD_OFFICE (in DEFECTS):
  - BARRIERS_DEFECT
    error message 'Barriers faulty'

There is no explicit control flow HEAD_OFFICE → BARRIER to indicate the repair of the barriers as it exists at the traffic lights and the sensor. This is explained in the barrier hardware section (see Sect. 5.3.2).

B.4 Sensor

The following list shows the control and information flows connected to the sensor. Since the sensor is not an interactive device there are no commands from the overall crossing control. Instead there is an information flow from the sensor control to CROSSING_CONTROL containing status messages:

- SENSOR_CONTROL → CROSSING_CONTROL (in SENSOR_REPLY):
  - PASSED
indicates that the train has passed
  - SENSOR_ERR
indicates a failure of the sensor

The software control of the sensor (SENSOR_CONTROL) receives information from the hardware to interpret them and requests test reports from the hardware:

- SENSOR_CONTROL → SENSOR (in SENSOR_HW_COMMANDS):
  - S_TEST
    request for test report
- SENSOR → SENSOR_CONTROL (in SENSOR_HW_REPLY):
  - SENSOR_ON
    indicates that the train is on the sensor
  - SENSOR_OK
    test report 'Sensor ok'
  - SENSOR_FAULTY
    test report 'Sensor faulty'

Analogous to the traffic lights (see Appendix B.2) there is some communication with the HEAD_OFFICE:

- SENSOR_CONTROL → HEAD_OFFICE (in DEFECTS):
  - SENSOR_DEFECT
    error message 'Sensor faulty'
- HEAD_OFFICE → SENSOR:
  - REPAIRED
    the fact that all hardware devices are repaired

Because the behavior of the sensor depends on the position of the train this information has to be passed to the sensor:

- ENVIRONMENT → SENSOR:
  - CUR_DATA
    the dynamic train data, therein the actual position of the train