EMBSYS 110 Module 5

Design and Optimization of Embedded and Real-time Systems

1 Basic QP Framework

1.1 QHsm Event Processor

Previously we have demonstrated how to implement a simple HSM named *Demo* using QP. This is a recap of the basic ideas:

1. Derive your application HSM class (e.g. Demo) from the QHsm base class provided by QP. (Note there can be immediately base classes.)
2. Implement each state as a member function of the HSM class.
3. Handle received events in each state function with a switch-case construct according to the rules defined in a statechart.

Since this is such a fundamental coding pattern, it's worth showing it again:

```
QState Demo::S21(Demo * const me, QEvt const * const e) {
    switch (e->sig) {
        case Q_ENTRY_SIG: {
            EVENT(e);
            return Q_HANDLED();
        }
        case Q_EXIT_SIG: {
            EVENT(e);
            return Q_HANDLED();
        }
        case Q_INIT_SIG: {
            EVENT(e);
            return Q_TRAN(&Demo::S211);
        }
        case DEMO_A_REQ: {
            EVENT(e);
            return Q_TRAN(&Demo::S21);
        }
        case DEMO_B_REQ: {
            EVENT(e);
            return Q_TRAN(&Demo::S211);
        }
```

```
        case DEMO_G_REQ: {
            EVENT(e);
            return Q_TRAN(&Demo::S11);
        }
    }
    return Q_SUPER(&Demo::S2);
}
```

QHsm is called an *event processor*. Its job is to process events ***dispatched*** to it (via its public member function *dispatch()*) according to the rules encoded in its state functions. Notice the keyword "***dispatched"*** is in passive voice, which means some other objects must call its dispatch() function to pass events to it. In other words a QHsm object does not actively grab events to process on its own. It is passive.

QHsm is useful by itself, since it handles all the complex transition rules in an arbitrarily complex state hierarchy. However will it be more useful if we can extend QHsm to become active? It is a very attractive idea, and without a better name we call such extended object an ***active object*** represented by *QActive* in QP.

Note – For a complete and formal description of the statechart semantics, see this:

https://www.researchgate.net/publication/2533509_On_the_Formal_Semantics_of_VisualSTATE_State charts

1.2 Active Object

By *active*, we want an active object to actively wait for events to arrive and dispatch them to an HSM on its own. What does it need to make this happen?

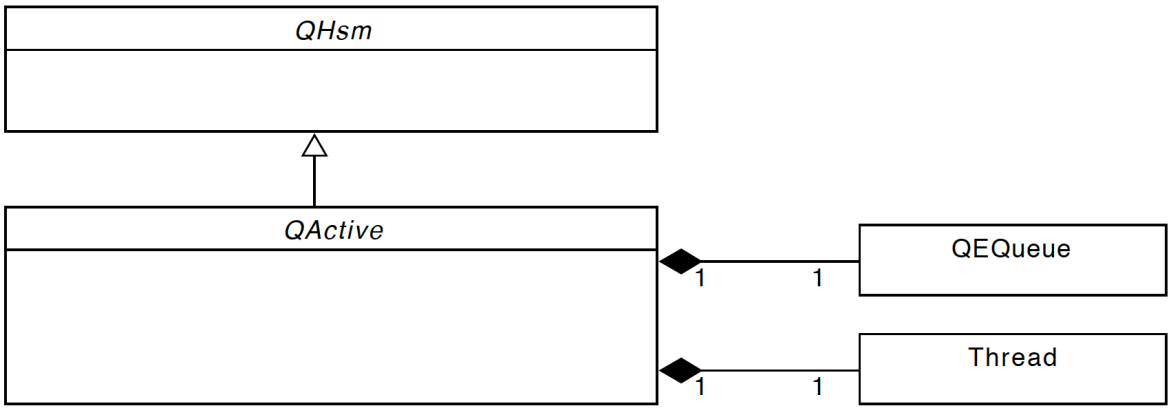
Just think about how you would normally do when using an RTOS. Mostly likely you would create a thread and have it block on an event queue for events for arrive. As long as the queue is non-empty, the thread will get the oldest event out of the queue to process. After each event it will loop back to check the queue again, and if the queue is empty it will block on it (i.e. the GetEvent() call will not return until an event arrives). This loop is called an event loop, and it typically looks like this:

```
void ThreadMain() {
    while (running) {                          // Event loop.
        QEvt const *e = eventQueue.GetEvent();  // Blocking call.
        switch (e->sig) {
            stateMachine.dispatch(e)           // Handles event in state-machine.
        }
    }
}
```

This pattern will probably show up many times in a project. Rather than crafting it from scratch every time it would be better for us to apply object-oriented design to:

1. Encapsulate related concepts together in a class, which means adding a *thread* and an *event queue* to a *hierarchical state-machine*. We call it QActive.
2. Enable code reuse by inheriting application specific classes from common reusable base classes (QHsm and QActive).

In a nutshell, an active object *is a* hierarchical state-machine that *has a* thread and *has an* event queue. As you recall we have talked about this relationship briefly when we studied class diagrams (about UserLed). Now we should understand what it is all about.



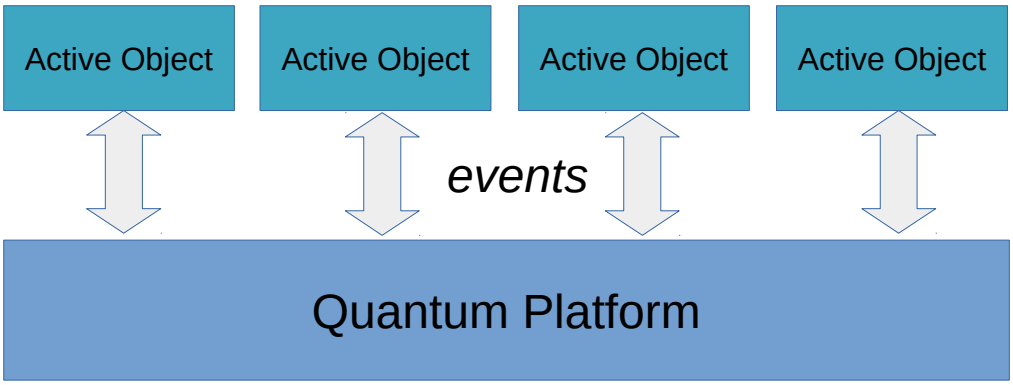
1.3 System Partitioning

Now we have learned an active object being a fundamental system component. It is natural to extend this idea to contemplate a software system as a collection (or a *partition as in set-theory*) of multiple active objects. Each active object is responsible for a certain area of concern, and hence yielding desirable separation of concerns or decoupling. They communicate with each together in one way or the other, and together they define the overall system behaviors.

It surely sounds simple, doesn't it? However it leads to two important questions:

1. How should we partition the system into active objects?
2. How should active objects communicate with each other?

It turns out these are difficult questions. They are difficult because they are very abstract. They are difficult because there are more than one ways of doing it, and it's hard to measure which way is optimal. Let's look at some common approaches suitable for real-time embedded systems. The first one to look at is the publish-subscribe model provided by QP as illustrated below.



In the publish-subscribe model, active objects communicate with each other via events. This is one kind of event-driven systems. QP serves as an event broker in this model. Active objects exchange events through QP. As a result, they do not call public methods (API) of other active objects directly, and therefore do not need to maintain references to other active objects. Maintaining references to other objects (a.k.a lifetime management) can be complicated since it can easily cause dangling pointers or memory leak issues.

An active object publishes an event via this QP API:

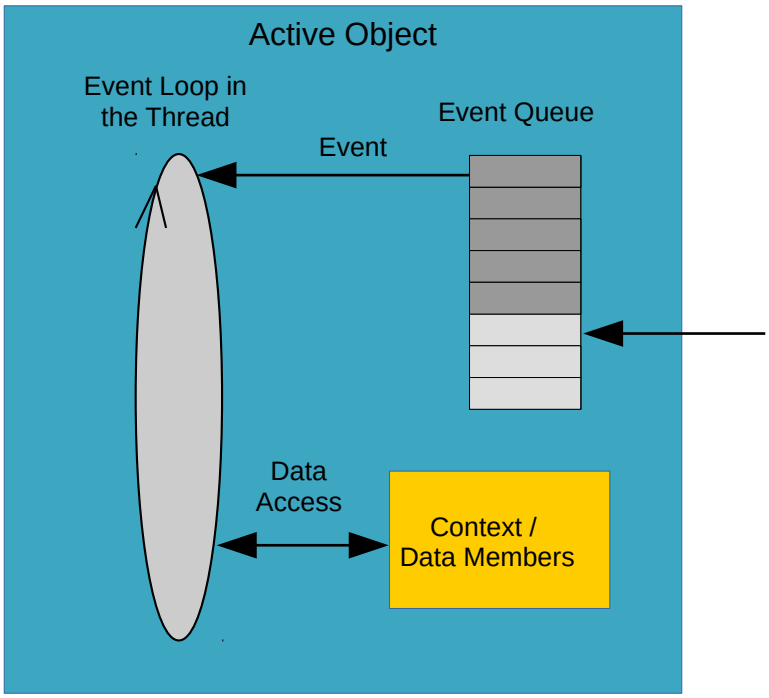
```
QF::publish_(QEvt const * const e)
```

QP will post this event to the event queues of any active objects that have subscribed to this event type via this API:

```
void QActive::subscribe(enum_t const sig)
```

The advantages of publish-subscribe include high degree of flexibility and decoupling since there are no linkages among active objects (i.e. there are no direct function calls from one object to another). It is very easy to drop in another component as long as it subscribes to the same events.

Another advantage of this type of event-driven architecture is that there is minimal or no sharing of data between threads, thanks to encapsulating a thread within the active object class which provides a context for the thread. That context, in form of data members of the class, includes everything the thread needs to access directly. When threads do not share data, there is little need to use mutex and the whole class of issues related to mutexes and data contention disappeared. The diagram below illustrates the concept of a localized context per active object.



Nevertheless, the broadcast nature of publish-subscribe can be problematic if we need to ensure reliability, since a publisher does not know who the subscribers are. It does not know if there is *none*, *one* or *multiple* recipients of a published event, and therefore it can be difficult to implement acknowledgement or return-event-path for guaranteed delivery or request-reply handshaking. If not careful one might be caught by race-condition issues that are very hard to track down.

2 Enhanced Framework

QP provides a higher level of abstraction over tradition RTOS primitives such as threads, queues, mutexes, etc. It allows us to focus on the more important aspects, i.e. the actual behaviors, rather than the low level interactions such as when we need to lock a mutex, whether a function call will block, what happens if one thread updates a data set while it is being shared by other threads, etc.

QP is intended to be a generic framework. It is flexible but can be minimal. When you use it in your projects you often need to provide a lot of external hooks and apply usage patterns. For example,

1. When creating an active object you need to allocate memory for its event queue externally.

2. To support orthogonal regions (i.e. multiple HSMs in one active object) you need to delegate events from the active object to each HSMs explicitly.
3. The built-in publish-subscribe mechanism may not fit your projects if you need strong synchronization among objects. You will need to apply some well-defined semantics to your event interface and customize the event delivery mechanism.
4. Though QP provides a debugging tool called QSPY, you may still want to add your own that is customized for your need.

To provide a slightly higher level of abstraction on top of QP, we introduce our own application framework layer, simply called *fw* in the name space of *FW*. You will find its source code under the folder *framework*.

2.1 Common Attributes

In QP there is no builtin identifiers for active objects or HSMs, except the C++ pointers to them. If you want to have a simple ID number or name to be associated with each active object or HSM, you would have to add a *m_id* or *m_name* field to each concrete class derived from QActive or QHsm. Over time you will have a collection of data members that are common to all your concrete classes. It is a perfect chance to apply encapsulation and use a class to contain all these common attributes.

We call this class *Hsm*, meaning that it contains attributes that are common to all hierarchical state-machines. It is defined in *framework/include/fw_hsm.h*. Below is an extract of the class definition:

```
class Hsm {
protected:
    enum {
        OUT_HSMN_SEQ_MAP_COUNT = 8,
        DEFER_QUEUE_COUNT = 16,
        REMINDER_QUEUE_COUNT = 4
    };
    Hsmn m_hsmn;
    char const * m_name;
    QP::QHsm *m_qhsm;
    char const *m_state;
    ...
}
```

The member *m_hsmn* means *HSM Number* which is a unique identification of each HSM instance in the system. It is enumerated statically in include/app_hsmn.h with the help of some macros:

```
#define APP_HSM \
    ADD_HSM(SYSTEM, 1) \
    ADD_HSM(CONSOLE, 2) \
    ...
    ADD_HSM(DEMO, 1) \
```

```
    ...
#define ALIAS_HSM \
    ADD_ALIAS(CONSOLE_UART2,    CONSOLE+0) \
    ADD_ALIAS(CONSOLE_UART1,    CONSOLE+1) \
    ...
```

In the list above `DEMO` is the HSMN (HSM Number) of the Demo active object we used to demonstrate the statechart example in the PSiCC book. The constructor of Demo passes the HSMN `DEMO` along with the corresponding name string `"DEMO"` to the constructor of the intermediate base class *Active*:

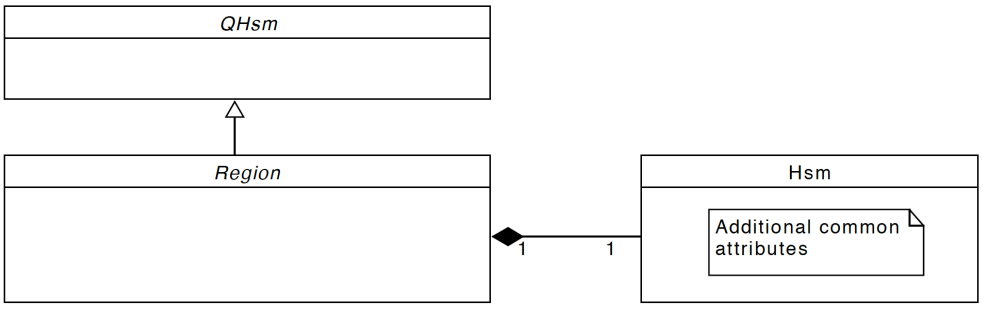
```
Demo::Demo() :
    Active((QStateHandler)&Demo::InitialPseudoState, DEMO, "DEMO"),
    m_stateTimer(GetHsm().GetHsmn(), STATE_TIMER) {
    SET_EVT_NAME(DEMO);
}
```

We will see in the next section what *Active* is and how it uses the HSMN passed to its constructor.

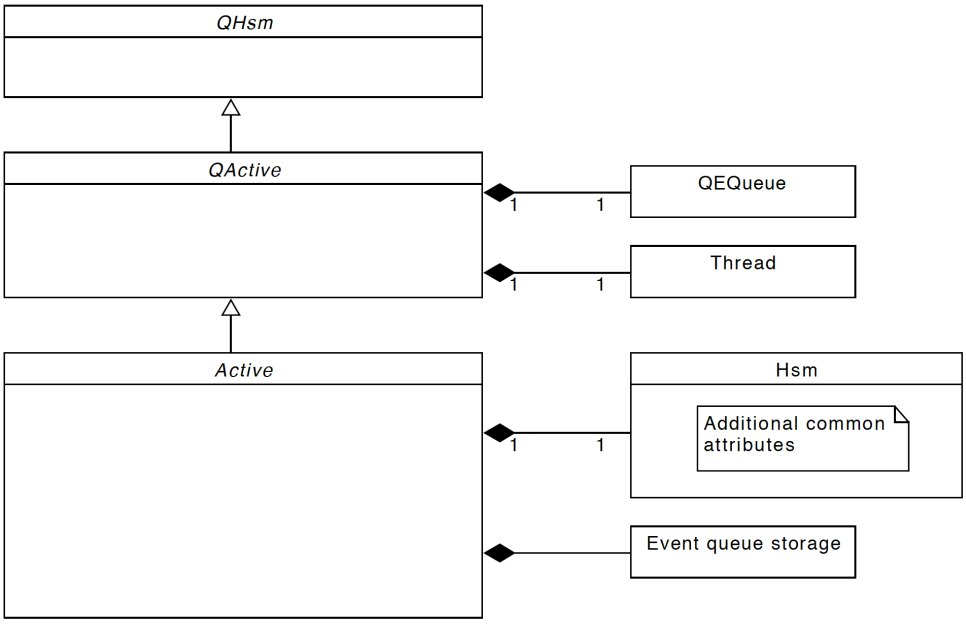
2.2 Region and Active

We introduced the class Hsm in the previous section, which is used to hold common attributes for all HSMs. We have also seen how QP uses the class QHsm to represent an HSM and how it derives QActive from QHsm to represent an active object.

Putting them all together, we derive a new class *Region* from QHsm, which allows us to extend the features of QHsm. One of the extensions is to compose an Hsm object to hold all the additional attributes. The class name *Region* comes from the statechart concept of *orthogonal regions* which can be viewed as concurrent hierarchical state-machines running in the same thread-context of an active object. In other words a Region *is an* QHsm composing an Hsm object as illustrated in the class diagram below:

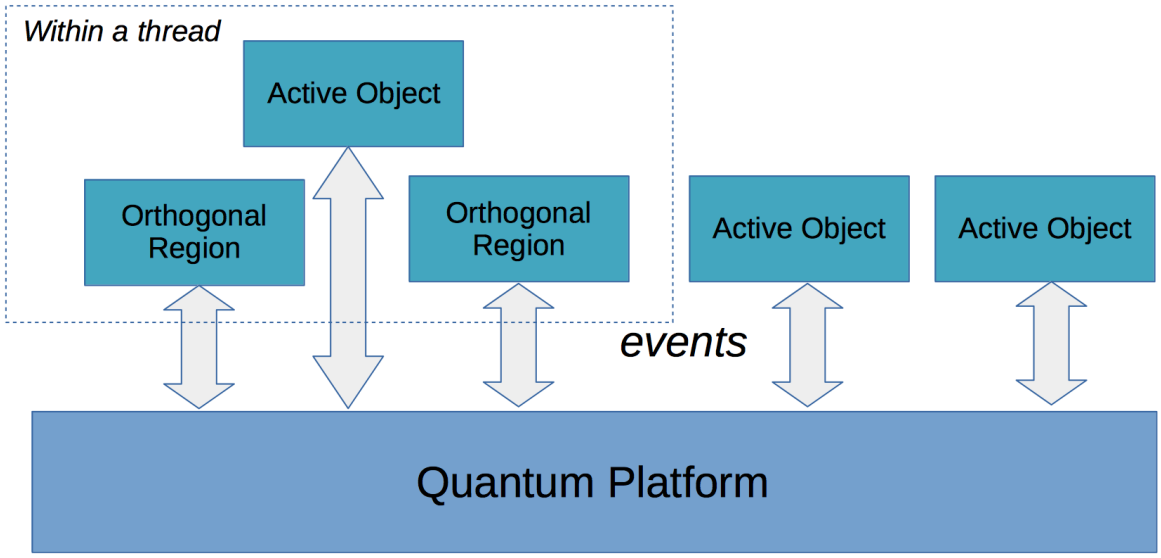


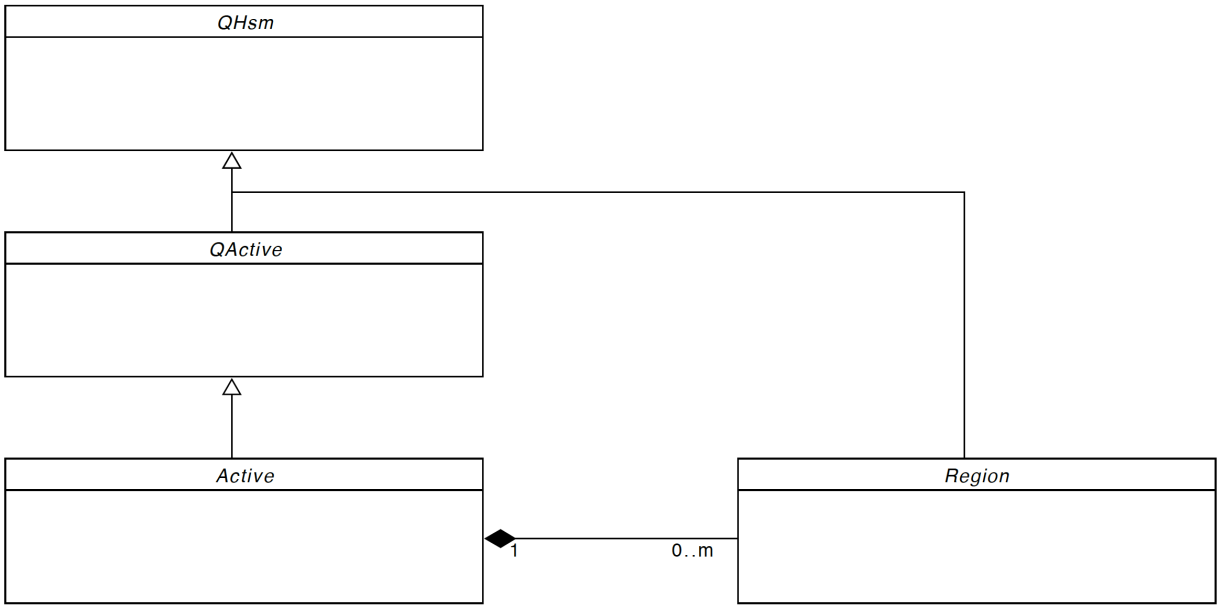
Similarly we extend QActive by deriving a new class *Active* from it. Active composes an Hsm object along with memory storage for the event queue making it easier to create an active object.



Now we have class Region representing our extended hierarchical state-machine (or orthogonal region) and class Active representing our extended active object. How about we combine them together? We can have an active object composing one or more Region objects to support concurrent state-machines running in the same thread, similar to orthogonal regions in a statecharts. (Note – An active object is by itself an HSM, and therefore you don't need to add a Region to it to implement a single HSM.)

The concept of orthogonal regions is illustrated in the block diagram and class diagram below:





For reference, the class definitions of Region and Active are listed below:

```
class Region : public QP::QHsm {
public:
    Region(QP::QStateHandler const initial, Hsmn hsmn, char const *name) :
        QP::QHsm(initial),
        m_hsm(hsmn, name, this),
        m_container(NULL) {}
    void Init(Active *container);
    void Init(XThread *container);
    Hsm &GetHsm() { return m_hsm; }
    virtual void dispatch(QP::QEvt const * const e);

protected:
    void PostSync(Evt const *e);
    ...
    Hsm m_hsm;
    QP::QActive *m_container;
};


class Active : public QP::QActive {
public:
    Active(QP::QStateHandler const initial, Hsmn hsmn, char const *name) :
        QP::QActive(initial),
        m_hsm(hsmn, name, this),
        m_hsmnRegMap(m_hsmnRegStor, ARRAY_COUNT(m_hsmnRegStor), ...){
    }
```

```
    void Start(uint8_t prio);
    void Add(Region *reg);
    Hsm &GetHsm() { return m_hsm; }
    virtual void dispatch(QP::QEvt const * const e);

protected:
    void PostSync(Evt const *e);
    enum {
        MAX_REGION_COUNT = 8,
        EVT_QUEUE_COUNT = 16
    };
    Hsm m_hsm;
    HsmnReg m_hsmnRegStor[MAX_REGION_COUNT];
    HsmnRegMap m_hsmnRegMap;
    QP::QEvt const *m_evtQueueStor[EVT_QUEUE_COUNT];
};
```

2.3 Event Interface

In an event driven system the definition of events is crucial and deserves deeper considerations. This includes the enumeration of event types and the corresponding event classes to carry event parameters. QP does not dictate how events are defined. In simple examples one global enumeration would suffice. However for larger projects this single list can be hard to maintain since it would easily contain more than a hundred events for the entire system.

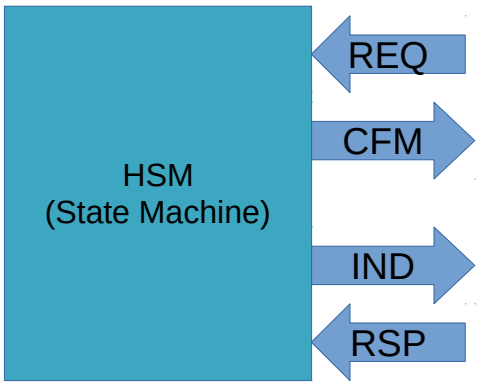
In many event driven systems the definition of events does not follow strong semantics. Most events use causal names like *SOMETHING*_HAPPENED, or DO_*SOMETHING*, etc. Due to the asynchronous nature of event driven systems, it can easily lead to race-conditions.

In our enhanced framework, we require each HSM (being a Region or an Active object) to define its own events. For each HSM there are three different kinds of events, namely

1. Interface events
2. Internal events
3. Timer events

2.3.1 Interface events

Interface events are used for communications among HSMs. Their naming convention follows strong semantic rules to give them clear and precise meanings. Each event must fall into one of the four categories, namely *request*, *confirmation*, *indication* or *response*. A request forms a pair with a confirmation, while an indication forms a pair with a response. Together they define the external interface of an HSM through which it communicates with other HSMs.



Interface events are defined in an *interface file* for each HSM, such as DemoInterface.h. We use macros to generate event names automatically and to partition the event space among all HSMs in the system. If additional event parameters are needed, dedicated event classes will be defined in the interface file as well.

```
#define DEMO_INTERFACE_EVT \
    ADD_EVT(DEMO_START_REQ) \
    ADD_EVT(DEMO_START_CFM) \
    ADD_EVT(DEMO_STOP_REQ) \
    ADD_EVT(DEMO_STOP_CFM) \
    ADD_EVT(DEMO_A_REQ) \
    ADD_EVT(DEMO_B_REQ) \
    ADD_EVT(DEMO_C_REQ) \
    ADD_EVT(DEMO_D_REQ) \
    ADD_EVT(DEMO_E_REQ) \
    ADD_EVT(DEMO_F_REQ) \
    ADD_EVT(DEMO_G_REQ) \
    ADD_EVT(DEMO_H_REQ) \
    ADD_EVT(DEMO_I_REQ)

#undef ADD_EVT
#define ADD_EVT(e_) e_,

enum {
    DEMO_INTERFACE_EVT_START = INTERFACE_EVT_START(DEMO),
    DEMO_INTERFACE_EVT
};

class DemoStartReq : public Evt {
public:
    enum {
        TIMEOUT_MS = 200
    };
```

```
    DemoStartReq(Hsmn to, Hsmn from, Sequence seq) :
        Evt(DEMO_START_REQ, to, from, seq) {}
};
...
```

Event names are generated in the source file, such as Demo.cpp:

```
#undef ADD_EVT
#define ADD_EVT(e_) #e_,

static char const * const interfaceEvtName[] = {
    "DEMO_INTERFACE_EVT_START",
    DEMO_INTERFACE_EVT
};
```

The constant string array `interfaceEvtName[]` is *automatically* generated by C macros (kind of like magic) to store the names of the events corresponding to those defined in the enumeration. It is then injected into the logging system (via the macro SET_EVT_NAME called in the constructor of Demo) to generate human-friendly log messages.

2.3.2 Internal events

Internal events are used within an HSM. They are posted by the same HSM that processes them. They are mainly used as *reminders* to itself. While interface events must be posted in FIFO order, internal events can be posted in either FIFO or LIFO order. When an event is posted in LIFO order, it is guaranteed that it will be the next one to be processed and it can be called a synchronous event. Internal events are defined in the protected scope of an HSM class, such as the following code in Demo.h:

```
#define DEMO_INTERNAL_EVT \
    ADD_EVT(DONE) \
    ADD_EVT(FAILED)

#undef ADD_EVT
#define ADD_EVT(e_) e_,

enum {
    DEMO_INTERNAL_EVT_START = INTERNAL_EVT_START(DEMO),
    DEMO_INTERNAL_EVT
};
```

2.3.3 Timer events

Like internal events, timer events are used within an HSM. It is posted by QP to an HSM upon expiration of a timer started by the same HSM. Timer events enable an HSM to wait or delay an action without blocking. They are defined in the protected scope of an HSM class, such as the following code in Demo.h:

```
#define DEMO_TIMER_EVT \
    ADD_EVT(STATE_TIMER)

#undef ADD_EVT
#define ADD_EVT(e_) e_,

enum {
    DEMO_TIMER_EVT_START = TIMER_EVT_START(DEMO),
    DEMO_TIMER_EVT
};
```

3 Design Heuristics

Event-driven systems are inherently asynchronous. If we are not careful we would easily run into race-conditions, resulting in different components being out-of-sync.

Consider the case in which the System Controller (A) sends a request MOTOR_START_REQ (REQ) to the Motor Controller (B). Think about the following design examples:

1. If A simply assumes B gets the REQ event immediately and successfully starts the motor , A and B will get out-of-sync if B was in an *inconvenient* state momentarily (e.g. *Stopping* state) and ignores the REQ, of if there is a hardware problem that prevents the motor to be started at all.
2. The above problem could be avoided by using a REQ/CFM pair, such that B will send the completion status back to A, and A will wait for the CFM event before moving on. (Note – At all time, A is not blocked, and therefore is able to process other events).
3. However, what if A does not get the CFM event from B? A could wait forever, which is obviously not a good design choice. Better options include (a) automatic retrying (b) reporting the error to the upper layer controller or to the end user, which/who may decide to retry. In either case, A may send another REQ to B. What if B's CFM to the first REQ has just been delayed, and now reaches A. A will think it's the CFM to the second REQ. Again this is a race-condition, as the parameters for the two requests may not the same (e.g. different speed, or worse different direction)!
4. The above problem can be mitigated by matching sequence numbers in REQ/CFM pairs, and

that is why add a sequence number in our Evt base class.

Based on the above observation, we have come to the following design heuristics:

1. Handle all request events in all states.
2. Use a well-defined event interface with REQ/CFM and IND/RSP.
3. Match sequence numbers in REQ/CFM and IND/RSP pairs.
4. Use timers in wait states.
5. Use defer and recall pattern. (See Samek's book)
6. Use reminder pattern. (See Samek's book)
7. Ensure requests entering safe-states are always accepted (i.e. must not be rejected).
8. Use *hierarchical control pattern* to organize components (HSMs) in the system (see Gomaa's book, Chapter 11.3.4). This is similar to the *part-whole* layered architecture proposed by Pazzi's papers.

4 Case Study (System Startup)

System start-up and shut-down are often tricky to get right. Being able to stop and restart the system all in software is a good test for system robustness. Try out the command "**sys stop**" followed by "**sys start**".

The *stop* command brings the entire system to a *stopped* state. The *start* command brings the system to an operational (*started*) state again. By design, the stop request should not fail, or it triggers assertion as a last resort to restore the system.

Review the statechart design of the *System* active object to see where some of the design heuristics mentioned above are applied.

5 Reference

1. Modeling Rover Communication Using Hierarchical State Machines with Scala. Klaus Havelund. September 2017. (http://rjoshi.org/bio/papers/tips-2017.pdf)
2. Systems of Systems Modeled by a Hierarchical Part-Whole State-Based Formalism. Luca Pazzi. June 2013. (https://www.researchgate.net/publication/236156084_Systems_of_Systems_Modeled_by_a_Hierarchical_Part-Whole_State-Based_Formalism)
3. Modularity and Part-Whole Compositionality for Computing the State Semantics of Statecharts. Luca Pazzi. June 2012.

(https://www.researchgate.net/publication/230838633_Modularity_and_Part-Whole_Compositionality_for_Computing_the_State_Semantics_of_Statecharts)

4. https://www.reactivemanifesto.org/