Objects and Synchronous Programming

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ABSTRACT: Clear structure, support for abstraction, reuse, and easy evolution, these are the striking features of the object-oriented approach. Formal description of the reactive behavior, making it possible to prove logical correctness, is the essence of the synchronous paradigm. This paper proposes to combine these two approaches. An introductory example presents the notion of a synchronous object. Then, various issues related to objects and synchrony are addressed. Finally, we report on our progress in building a complete design and programming environment. Editors, compilers, simulators, and interfaces towards model checkers are integrated within this environment, which should contribute to better software quality in the field of real-time.

KEY WORDS: object-oriented, synchronous programming, reactive systems, reactive objects, real time systems, synchronous objects.

1. Introduction

The object paradigm is well adapted to complex system programming. Its main advantage is the improvement in program architecture. This improvement is obtained first by a modular decomposition based on real entities used by the application (the
objects) and, second, by a clear separation between the (abstract) interface for using an object and the details about its implementation (internal design). Powerful mechanisms such as aggregation, inheritance, polymorphism allow to benefit from this decomposition. As a consequence, the system is endowed with extensibility and reusability, thus favoring evolution and maintenance.

So far, object-oriented programming has been applied mostly to transformational systems that is, systems that compute at their own (internal) speed. Opposite to these, there exist reactive systems [HAR 85], which have permanent interactions with their environment at a rate imposed by the environment itself. Most reactive systems are also real-time systems (i.e., their reactions are temporally constrained).

Synchronous programming [BEN 91] was introduced as a solution to reactive programming requirements. Synchronous languages are founded on simple and rigorous mathematical semantics. Hence, one can build efficient and safe compilers. In addition, the logical correctness of programs can be proved formally. However, synchronous languages are mainly used to describe the control part of (reactive) systems. For other aspects of programming (data representation and transformation) they use classical (algorithmic) languages. Moreover, for an effective execution of the code generated by a synchronous language compiler, the user must provide an execution machine [AND 93].

Our objective is to combine the synchronous and object-oriented approaches in order to design complex reactive systems. The combination may impact several phases of the software life cycle: requirement analysis, preliminary and detailed design, implementation, testing, verification and validation...

This paper is organized as follows:

– We first recall the characteristics of the object-oriented approach.
– We then introduce an example: the modeling of the different operating modes of a cassette player/recorder. This example is composed of classical objects and of controllers modeled by synchronous objects.
– In part three, we present the synchronous object paradigm.
– The fourth part deals with communication between objects.
– And finally, we give an overview of a software workbench designed for programming with synchronous objects.

2. Characteristics of the Object-Oriented Approach

Using the object-oriented approach means considering the system to be developed as a collection of discrete cooperating objects. These objects are subsystem abstractions integrating data (state) and operations on these data (methods). Data are encapsulated, they cannot be accessed directly but only through a call to a method of the corresponding object. Hence, each object is responsible for its own data, that is for its own state and thus, for its own behavior. The list of methods for a given object constitutes the interface to manipulate (to use) the object; that is the only information that other (non-related) objects have to know about.

Object-oriented analysis and design methods (e.g., OMT) usually distinguish
three models [RUM 91]:

1. The object model, properly speaking, often termed also as the class model\(^1\), which describes the system objects, their usage interface, and the (static) relationships that exist between objects;
2. The dynamic model (or behavioral model), which specifies the (dynamic) interactions between objects on the one hand, and the reactive behavior of individual objects on the other hand;
3. The functional model, which deals with data transformation and computation.

One of the major attractions of the object-oriented approach is its power of abstraction: it makes it possible to express what changes in the system without having to describe how these changes occur. Adding or removing objects is rather easy. Similarly, modifying an object locally is straightforward, provided that the modification disturbs neither the interface of the object nor the relationships of the object with other objects. Thus, incremental development (adding objects), reusability, and maintainability (local modifications) are among the main benefits of the approach.

3. An Example

Our aim is to model and simulate the operations carried out by a play-record cassette\(^2\). The device is composed of two decks (Deck1 is play-only, and Deck2 is play-record). Playback and recording operations offer sophisticated options involving sequences of simpler operations (e.g., continuous play from deck to deck, auto-reverse copy, blank skipping...).

We model this cassette recorder as a collection of cooperating reactive objects. Some objects are imposed by the application. So are sensors (push button, limit switches...) and actuators (motors, magnetic heads, LEDs...). A cassette can be conveniently abstracted by a class, which captures both the attributes of the tape and its access methods.

Contrary to approaches like SA/RT, which consider controllers apart from data flows, we assimilate controllers to objects. Of course, they are highly reactive objects. ROOM [SEL 94] adopts a similar point of view, where controllers are instances of “actors” (active objects).

Through this example, we will stress two major issues:

- class modeling (interest and limitations),
- dynamic behavior representation.

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\(^1\) Indeed, most object-oriented analysis and design methods are class-based; a class represents the properties common to a set of similar objects that is, it represents the type of an object. Then models use classes instead of individual objects.

\(^2\) This example is inspired from an unpublished experiment performed by Frédéric BOUSSINOT with Reactive Objects [BOU 95].
In this kind of application, functional aspects are limited and will be ignored here.

3.1. The Class Model

Figure 1 presents a class model à la OMT for one of the application objects: the magnetic tape. In fact, there are two sorts of magnetic tapes: the tape properly speaking (Passive_Tape) and the tape once it has been loaded into the deck (Tape_in_Deck). The first object is rather passive: its only dynamic property is the possibility to break. The second object, the tape inserted into a deck, enriches both the data structure and the behavior of the first: selection of the side and of the motion direction, handling of the “end of tape” (eot) event. Inheritance (denoted by a triangle in OMT) is suited to represent such a specialization. It is then possible to derive other kinds of tape, like the ones which have a label (Labeled_Tape) or even the tapes that spontaneously vanish into smoke (the “Mission Impossible” tapes!). As indicated on figure 1, multiple inheritance makes it possible to represent these new tapes once inserted into the deck\(^4\).

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\(^3\) This “spontaneous” event emission is not directly representable in an OMT class model. Thus we have enriched the OMT notation, as can be seen on figure 1.

\(^4\) Note the use of the OMT “black triangles” representing virtual multiple inheritance as in C++: there will be only one copy of the base class (here Passive_Tape) in the derived classes, whatever the number of the inheritance paths happens to be.
When it comes to representing the deck itself, the situation gets a little trickier. Of course, we wish to consider a play-record deck as a specialization (a derivative) of a play-only deck. The components of a deck (controller, motor(s), head(s)) may be represented with an aggregation as in figure 2. Note that the association between the deck and the tape is not an aggregation, but a simple (abstract) association (load). Indeed the tape and the deck are perfectly independent objects; each of them may live on its own.

However, there is a problem with the model in figure 2. If a simple controller (Read_Controller) is sufficient for a read-only deck, the full deck must accommodate a more complete controller (Full_Controller). This situation is not directly representable in OMT: in figure 2, we represented it with a constraint on a derived aggregation. Another possible model is to derive the deck from the controller, as in figure 3. This may appear somewhat illogical, since a deck is not a (specialization of a) controller. Hence, we use private inheritance (that we represent by a small bar crossing the association). One can note the elegant symmetry of the scheme: multiple inheritance makes it possible to correctly represent the structure of the play-record deck compared to the play-only one.

Here, we meet a classical situation (and a huge matter of discussion) in the object-oriented approach: inheritance may be used both with the semantics of subtyping or as a simple means to share implementation (code). The discussion about these issues is beyond the scope of this paper.

To complete the model, the player-recorder itself is merely the aggregation of two decks: Deck1 is an instance of class Player, whereas Deck2 is an instance of PlayerRecorder.

The OMT-like models do not show precisely the exchange of messages and
events between objects\textsuperscript{5}. We thus introduced a new type of diagram to make these dynamic links explicit (figure 4). On these diagrams boxes represent objects. Input ports ( ) and output ports ( ) represent methods. Connections are directed from an input port to an output one; they represent point-to-point communications. The aspects related to communications will be described in section 5. Note that in order to keep the diagram legible, several signals may be grouped together to form “buses”. This is the case for output signals from object \texttt{keyboard} (play...record) which are also found as input to \texttt{Controller}.

### 3.2. The Dynamic Model

The behavior of each object is expressed by the “dynamic model”. Usually, graphical representations are used (State graphs, STATECHARTS in OMT, ROOM-charts in ROOM...). We adopt the SYNCHARTS \cite{AND96}, a new model derived from STATECHARTS \cite{HAR85} and Argos \cite{MAR91}. The SYNCHARTS are state-based models suited to reactive behavior modeling. They support hierarchy of states, orthogonality, information broadcasting and preemptions. On the last point, SYNCHARTS definitely surpass STATECHARTS: they make a clear distinction between

\textsuperscript{5} This is somewhat unfair. Classical OMT dynamic model includes the description of the exchange of messages through the use of event-trace diagrams, but this description is not global to the system, it is scenario-based. Also forthcoming versions of OMT may include a system-wide description of messages and events exchange.
various kinds of preemptions (abortion or suspension, weak or strong, see [BER 92]).

A detailed presentation of the SYNCCHARTS is beyond the scope of this paper. We shall only comment two examples of synccharts. They are sufficient to introduce several key features of the model.

The syncchart in figure 5 expresses the behavior of the basic play-record controller. Two macro states, named Normal_M_Ctrl and Basic_Ctrl, have concurrent evolutions. The dotted line in figure 5 separates the two orthogonal components. The behavior of the motor control (Normal_M_Ctrl macrostate) is given in figure 6.

An arc between two states stands for abortion: as soon as the event associated with the arc occurs, the source state is exited and the target state is entered. An ordinary arc denotes a weak abortion: the preempted macrostate may execute its “last wishes” before being killed. An arc with a small circle at its origin denotes a strong abortion: the preempted state is not allowed to execute any reaction. Note that both weak and strong abortions are instantaneous and synchronous with the occurrence of the triggering event.

The behavior of a syncchart is fully deterministic. If several events can abort a macrostate, a priority order must be given (by small integer numbers next to the transition). In Basic_Ctrl, event rec is given the highest priority, event rewind the lowest.

A synchronous model, like SYNCCHARTS, relies on the notion of an instant. There is a clear distinction between strictly future and present-or-future occurrences. The symbol “#”, which prefixes some events, stands for the latter case (e.g., #rec in the Basic_Ctrl_State means that if rec is present when entering this macrostate,
then the component state $Rec_{Ctrl}$ must be entered immediately). The absence of prefix \# requires that only a strictly future occurrence be considered.

The evolution of a syncchart is controlled by triggering events (event-driven systems). Conversely, a syncchart can act upon its environment (output events). In SYNCCHARTS as in Moore machines, outputs can be associated with states: a signal identifier written in an ellipse (a state) indicates that this signal is emitted whenever the state is active. For example, when the state $Wind_{Ctrl}$ is active, $MFF$ (Motor Fast Forward) is sustained, so that a tape can be wound. A syncchart can also emit signals while a transition is taken, as in a Mealy machine. This possibility is not shown in the given examples.

Figure 5. Control of the play-record deck.

An emitted signal may be hidden from the environment and used for internal pur-
poses (synchronization). Signals $M_{\text{pause}}$, $M_{\text{stop}}$, $M_{\text{toggle}}$ are local to the macro state $\text{PlayRec\_Ctrl}$. When in the Idle state, $\text{Basic\_Ctrl}$ emits the local signal $M_{\text{stop}}$ that influences the behavior of the motor controller. Since a signal may convey a value, local (valued) signals are also used for internal communication.

In figure 6, special arcs are drawn: they have no source state, they target a state, and they end by a small circle head. We call them suspension arcs. When the event associated with a suspension arc is present, the target state is “frozen”, just as if time did not flow with respect to the internal evolutions of the state (e.g., when $M_{\text{stop}}$ is present, the nested state graph can neither change state, nor emit signals). A suspension can be immediate (e.g. $M_{\text{stop}}$ in $\text{Normal\_M\_Ctrl}$), or strictly future (e.g. $M_{\text{toggle}}$).

To sum up, the S\textsc{ync}C\textsc{harts} are suitable for modeling sophisticated reactive behaviors. They promote preemption as a first class concept, so that normal as well as abnormal behaviors can be easily specified. Moreover, S\textsc{ync}C\textsc{harts} rely on a formal semantics [AND 96-1] and they can be compiled into equivalent E\textsc{sterel} programs (program 1 is an E\textsc{sterel} program equivalent to the $\text{Normal\_M\_Ctrl}$ syncchart of figure 6). Thus, S\textsc{ync}C\textsc{harts} may be seen as a graphical variant of the E\textsc{sterel} language.

4. Synchronous Objects

As we saw in section 2, the object-oriented approach is a powerful abstraction

```plaintext
module Normal_M_Ctrl:
  input Mstop, Mpause, Mtoggle;
  output MF, MB;
  suspend
  loop
    do
      suspend
        sustain MF
      when immediate Mpause
        watching Mtoggle;
      do
        suspend
          sustain MB
        when immediate Mpause
          watching Mtoggle
        end loop
    when immediate Mstop
end module
```

**Program 1. Example of translation of a S\textsc{ync}C\textsc{hart} to E\textsc{sterel}.

synchart of figure 6). Thus, S\textsc{ync}C\textsc{harts} may be seen as a graphical variant of the E\textsc{sterel} language.
tool. It allows us to say *what* changes without necessarily specifying *how* it changes. The synchronous approach gives a similar level of abstraction for the specification of the behavior of modules interact.

In the synchronous model, signals are abstractions of communications. They are instantaneously broadcast throughout the system. Thus they constitute the medium through which concurrent subsystems communicate. Arbitrarily complex interactions may be represented easily. The synchronous composition of the subsystems can be defined rigorously and has interesting properties such as the determinism of the parallel composition.

As the tape deck example shows, an application may use both transformational and synchronous reactive entities. The object-oriented approach permits the integration of both kinds of entities by encapsulating the synchronous code into objects. Synchronous modules are well suited to this encapsulation since they communicate only through their signals and thus can be considered as black boxes.

So, the first step is to turn a synchronous module into a class that we call a *synchronous class*. Instances of this class have the same reactive behavior as the original synchronous module. All the synchronous classes derive from an abstract class named *Synchronous* that defines the basic protocol of any synchronous object. With this basic protocol we can define a synchronous execution machine that preserves the synchronous semantics of the modules in the object-oriented language.

This allows synchronous objects to be interconnected and to communicate synchronously. The behavior of such a network of synchronous objects is identical to the behavior of a synchronous program built with the corresponding modules. Hence, synchronous class libraries can be used to build programs without needing a synchronous language compiler, and so, without needing the source code of the modules. Of course, this separate compilation has limitations: the directed interconnection graph of the objects must be acyclic, except when a non-instantaneous dependency is explicitly stated, such as for a delay. Indeed, checking the causality of communication loops requires the knowledge of the semantics of the modules—we have to “open the black box”.

### 5. Communication between Objects

Regular objects communicate through messages. Synchronous objects are objects but they have a synchronous reactive part which communicates only through signals. So we have to define new protocols to transport signals within messages between synchronous objects, and to make signals accessible through messages for the communication between synchronous objects and regular objects.

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6 An abstract class is a class with methods the implementation of which is deferred to derived classes. Such a class cannot be instantiated. It defines an interface subset shared by all its subclasses.
5.1. Synchronous Communication and Clocks

Synchronous communication between objects implies that the objects which communicate together share the same notion of an instant. The execution machine implements this notion with the Clock class. Several instances of this class (that is several “clocks”) may be used in the same program in order to process events that occur at different time scales. Each clock determines a scheduling of the objects it manages according to their connections and makes them react in an order that satisfies their dependencies. All the objects managed by the same clock constitute the clock domain.

Contrary to ESTEREL in which synchronous communication is expressed by “name sharing” (all the signals that share the same name have the same value), synchronous communication between synchronous objects is a point to point communication, and several input signals can be connected to a same output signal. The reason is the following: when two objects are instantiated from the same class, their signals bear the same name although they correspond to independent entities; hence, they must not be connected. Therefore, the name sharing scheme cannot be used. Thus, input signals have a connection method that takes an output signal as argument and allows the explicit declaration of the connections between synchronous objects.

This point to point connection scheme makes it possible to use the type checking mechanisms of C++ [STR 86] to ensure that an input signal can only be connected to an output signal of the same type.

5.2. Asynchronous Communication

Synchronous objects must be able to communicate with regular objects or with synchronous objects belonging to another clock domain. So we need a mechanism for asynchronous communication. Communications leaving a clock domain are not really an issue since one can read the value of the output signals of a synchronous object without disturbing it. On the other hand, communications entering a clock domain require a synchronization phase: we must build a synchronous event from one or several asynchronous events.

Turning asynchronous events into synchronous events is not a trivial task. It is carried out by interface objects [BOU 93]. These special synchronous objects are sensitive to asynchronous events that activate some of their methods, and they produce synchronous events for the other objects related to the same clock. Such objects may be written in C++ or in a synchronous language. In the latter case, nothing should be assumed about the simultaneity of the inputs since this notion has no meaning for asynchronous events.

5.3. Dynamicity

We have seen that synchronous objects can be interconnected and can communicate synchronously under the control of a clock. For such a group of objects (a clock domain), it is always possible to write an equivalent program in a synchronous lan-
guage, and to use proof tools to check some properties. The object-oriented approach brings the reusability and facilitates the integration. But once a synchronous module has been translated into a C++ class, nothing forbids to dynamically create or destroy instances of this class during the execution of a program. For this, we must be able to dynamically change the connection graph, disconnecting deleted objects and connecting newly created ones.

We then reach a higher order of description since an event not only triggers the reaction of an object but may trigger a “clock reaction” — a modification of the equivalent synchronous program.

The main drawback of dynamicity is the lack of a synchronous program equivalent to a dynamic clock. This forbids the use of classical proof tools to check properties on the behavior of this clock. But dynamicity allows us to express synchronous behaviors that cannot be expressed in a synchronous language while still benefiting from the synchronous approach for the development of the components of the system and for the control of dynamicity.

Dynamicity may also be used in systems where the number of objects to manage is not known beforehand. Examples of use of dynamicity are presented in the thesis of Frédéric BOULANGER [BOU 93].

6. Software Workbench

To support our approach to object-oriented synchronous programming, we are developing a platform that integrates several software applications dedicated to synchronous programming (editors, compilers, simulators, code generators, and proof systems). Figure 7 presents the main components of our platform described in detail in another paper [AND 96-2].

6.1. Editors

The description of a synchronous object can be either textual or graphical. Classical textual editors are used for C++, ESTEREL, MDLC [BOU 93] programs. On the other hand, we have developed our own graphical editors for GRAFCET [AND 94] and SYNCCHARTS.

6.2. Compilers

Synchronous modules can be specified by synchronous languages (LUSTRE or ESTEREL) as well as by synchronous formalisms (GRAFCET or SYNCCHARTS). Compiling a synchronous module is a complex task, which involves various compilers (see Figure 7). LUSTRE, ESTEREL, GRAFCET, SYNCCHARTS compilers yield an intermediate common code known as the OC code. OCC++ [BOU 93], another compiler, then turns the OC file to a C++ synchronous class. The reactive synchronous code is embedded within the synchronous class. It is accessible through the standard interface that we have developed for synchronous objects.
OCC++ can also generate a module description file (interface, source file...).

MDLC (Module Description Language Compiler) supports the creation of new classes by composition and derivation. The Module Description Language (MDL) allows us to define new modules by static connections between and derivations from existing modules. A derived class inherits the behavior of its super-class and may have additional input or output signals. MDLC produces a C++ synchronous class from an MDL description.

A library of classes, called LIBSYNC, provides the execution environment necessary for synchronous classes generated by OCC++ or MDLC.
6.3. Simulators

At each stage of the development, reactive behaviors can be tested. Simulators, automatically generated from synchronous objects, make it easy to analyze reactions to stimuli. Their graphical interfaces developed with Tcl-Tk [OUS 94] offer friendly animation.

A deeper insight in the program dynamics is brought about by interactive simulations with visualization of the execution at the source level (backward-mapping to source). It is all the more useful since representations describe concurrent executions. Such simulations can be performed on ESTEREL programs (XES simulator) and GRAFCET (GRANNY simulator) [AND 96-3].

6.4. Proof Tools

A synchronous program written in LUSTRE, ESTEREL, GRAFCET, SYNCCHARTS can be compiled into a finite automaton or a system of equations. On these representations, proof tools can be applied. Automata are analyzed by AUTO [DES 89], MEC [ARN 94], or TEMPEST [JAG 95]. Boolean equation systems are by-products of Boolean LUSTRE programs and GRAFCET. The safety properties of such systems are efficiently tested by a specific tool: the BAC (Boolean Automaton Checker) model checker [HAL 94] [AND 96-3].

7. Conclusion

Combining the object-oriented approach and reactive system modeling is an emerging domain of research. A few works have started to explore this promising field (ROOM method [SEL 94], O-Charts [HAR 94], Reactive Objects [BOU 95]). This paper aims at presenting a new pioneering contribution.

The first advantage of the synchronous object approach is to make it easier to model complex reactive systems. The object view relies on well-known analysis and design methods (e.g., industrial standards like OMT) and the behavior description benefits from the rigorous semantics of the synchronous model.

In order to gain the most from this method, it is essential to have a complete development platform. At present, this objective is partially fulfilled. In particular, tools for code generation are available, the target language being another industrial standard (C++).

This environment could not be complete without simulators and automatic links to formal proof tools. For this purpose, we provide interfaces with several model checkers.

We are convinced that the synchronous object approach will be the basis for numerous further developments and will contribute to improving the software quality indispensable for critical real time systems.
Bibliography


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Charles J. ANDRÉ received his “Doctorat d’État” in Electrical Engineering from the University of Nice (France) in 1981. Since 1983, he has been a professor of Automatic Control and Computer Science, and since 1989, the Head of the Electrical Engineering Department of the University of Nice. He also heads the SPORTS research team in the I3S laboratory. The topic of his thesis was the theory of Petri nets. His application domain has evolved to real-time systems and especially to their synchronous programming.

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