Synthesizing State-Based Object Systems from LSC Specifications

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Abstract. Live sequence charts (LSCs) have been defined recently as an extension of message sequence charts (MSCs; or their UML variant, sequence diagrams) for rich inter-object specification. One of the main additions is the notion of universal charts and hot, mandatory behavior, which, among other things, enables one to specify forbidden scenarios. LSCs are thus essentially as expressive as statecharts. This paper deals with synthesis, which is the problem of deciding, given an LSC specification, if there exists a satisfying object system and, if so, to synthesize one automatically. The synthesis problem is crucial in the development of complex systems, since sequence diagrams serve as the manifestation of use cases — whether used formally or informally — and if synthesizable they could lead directly to implementation. Synthesis is considerably harder for LSCs than for MSCs, and we tackle it by defining consistency, showing that an entire LSC specification is consistent iff it is satisfiable by a state-based object system, and then synthesizing a satisfying system as a collection of finite state machines or statecharts.

1 Introduction

1.1 Background and Motivation

Message sequence charts (MSCs) are a popular means for specifying scenarios that capture the communication between processes or objects. They are particularly useful in the early stages of system development. MSCs have found their way into many methodologies, and are also a part of the UML [UMLdocs], where they are called **sequence diagrams**. There is also a standard for the MSC language, which has appeared as a recommendation of the ITU [Z120] (previously called the CCITT).

Damm and Harel [DH99] have raised a few problematic issues regarding MSCs, most notably some severe limitations in their expressive power. The semantics of the language is a rather weak partial ordering of events. It can be used to make sure that the sending and receiving of messages, if occurring, happens in the right order, but very little can be said about what the system actually does, how it behaves when false conditions are encountered, and which scenarios are forbidden. This weakness prevents sequence charts from becoming a serious

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means for describing system behavior, e.g., as an adequate language for substantiating the use-cases of [J92,UMLdocs]. Damm and Harel [DH99] then go on to define **live sequence charts** (**LSC**s), as a rather rich extension of MSCs. The main addition is **liveness**, or **universality**, which provides constructs for specifying not only possible behavior, but also necessary, or mandatory behavior, both globally, on the level of an entire chart and locally, when specifying events, conditions and progress over time within a chart. Liveness allows for the specification of "anti-scenarios" (forbidden ones), and strengthens structuring constructs like as subcharts, branching and iteration. LSCs are essentially as expressive as statecharts. As explained in [DH99], the new language can serve as the basis of tools supporting specification and analysis of use-cases and scenarios — both formally and informally — thus providing a far more powerful means for setting requirements for complex systems.

The availability of a scenario-oriented language with this kind of expressive power is also a prerequisite to addressing one of the central problems in behavioral specification of systems: (in the words of [DH99]) to relate scenario-based inter-object specification with state machine intra-object specification. One of the most pressing issues in relating these two dual approaches to specifying behavior is **synthesis** , i.e., the problem of automatically constructing a behaviorally equivalent state-based specification from the scenarios. Specifically, we want to be able to generate a statechart for each object from an LSC specification of the system, if this is possible in principle. The synthesis problem is crucial in the development of complex object-oriented systems, since sequence diagrams serve to instantiate use cases. If we can synthesize state-based systems from them, we can use tools such as Rhapsody (see [HG97]) to generate running code directly from them, and we will have taken a most significant step towards going automatically from instantiated use-cases to implementation, which is an exciting (and ambitious!) possibility. See the discussion in the recent [H00]. And, of course, we couldn't have said this about the (far easier) problem of synthesizing from conventional sequence diagrams, or MSCs, since their limited expressive power would render the synthesized system too weak to be really useful; in particular, there would be no way to guarantee that the synthesized system would satisfy safety constraints (i.e., that bad things — such as a missile firing with the radar not locked on the target — will not happen).

In this paper we address the synthesis problem in a slightly restricted LSC language, and for an object model in which behavior of objects is described by state machines with synchronous communication. For the most part the resulting state machines are orthogonality-free and flat, but in the last section of the paper we sketch a construction that takes advantage of the more advanced constructs of statecharts.

An important point to be made is that the most interesting and difficult aspects in the development of complex systems stem from the interaction between different features, which in our case is modeled by the requirements made in different charts. Hence, a synthesis approach that deals only with a single chart — even if it is an LSC — does not solve the crux of the problem.

The paper is organized as follows. Section 2 introduces the railcar system of [HG97] and shows how it can be specified using LSCs. This example will be used throughout the paper to explain and illustrate our main ideas. Section 3 then goes on to explain the LSC semantics and to define when an object system satisfies an LSC specification. In Section 4 we define the **consistency** of an LSC specification and prove that consistency is a necessary and sufficient condition for satisfiability. We then describe an algorithm for deciding if a given specification is consistent. The synthesis problem is addressed in Section 5, where we present a synthesis algorithm that assumes fairness. We then go on to show how this algorithm can be extended to systems that do not guarantee fairness. (Lacking fairness, the system synthesized does not generate the most general language as it does in the presence of fairness.) In Section 6 we outline an algorithm for synthesizing statecharts, with their concurrent, orthogonal state components.

1.2 Related Work

As far as the limited case of classical message sequence charts goes, there has been quite some work on synthesis from them. This includes the SCED method [KM94,KSTM98] and synthesis in the framework of ROOM charts [LMR98]. Other relevant work appears in [SD93,AY99,AEY00,BK98,KGSB99,WS00]. The full paper [HKg99] provides brief descriptions of these efforts.[1] In addition, there is the work described in [KW00], which deals with LSCs, but synthesizes from a single chart only: an LSC is translated into a timed Büchi automaton (from which code can be derived).

In addition to synthesis work directly from sequence diagrams of one kind or another, one should realize that constructing a program from a specification is a long-known general and fundamental problem. There has been much research on constructing a program from a specification given in temporal logic.

The early work on this kind of synthesis considered *closed systems*, that do not interact with the environment [MW80,EC82]. In this case a program can be extracted from a constructive proof that the formula is satisfiable. This approach is not suited to synthesizing *open systems* that interact with the environment, since satisfiability implies the existence of an environment in which the program satisfies the formula, but the synthesized program cannot restrict the environment. Later work in [PR89a,PR89b,ALW89,WD91] dealt with the synthesis of open systems from linear temporal logic specifications. The realizability problem is reduced to checking the nonemptiness of tree automata, and a finite state program can be synthesized from an infinite tree accepted by the automaton.

In [PR90], synthesis of a distributed reactive system is considered. Given an architecture — a set of processors and their interconnection scheme — a solution to the synthesis problem yields finite state programs, one for each processor, whose joint behavior satisfies the specification. It is shown in [PR90] that the realizability of a given specification over a given architecture is undecidable.

[1] See technical report MCS99-20, October 1999, The Weizmann Institute of Science, at http://www.wisdom.weizmann.ac.il/reports.html.

Previous work assumed the easy architecture of a single processor, and then realizability was decidable. In our work, an object of the synthesized system can share all the information it has with all other objects, so the undecidability results of [PR90] do not apply here.

Another important approach discussed in [PR90] is first synthesizing a single processor program, and then decomposing it to yield a set of programs for the different processors. The problem of finite-state decomposition is an easier problem than realizing an implementation. Indeed, it is shown in [PR90] that decompositionality of a given finite state program into a set of programs over a given architecture is decidable. The construction we present in Section 5 can be viewed as following parts of this approach by initially synthesizing a global system automaton describing the behavior of the entire system and then distributing it, yielding a set of state machines, one for each object in the system. However, the work on temporal logic synthesis assumes a model in which the system and the environment take turns making moves, each side making one move in its turn. We consider a more realistic model, in which after each move by the environment, the system can make any finite number of moves before the environment makes its next move.

2 An Example

In this section we introduce the railcar system, which will be used throughout the paper as an example to explain and illustrate the main ideas and results. A detailed description of the system appears in [HG97], while [DH99] uses it to illustrate LSC specifications. To make this paper self contained and to illustrate the main ideas of LSCs, we now show some of the basic objects and scenarios of the example.

The automated railcar system consists of six terminals, located on a cyclic path. Each pair of adjacent terminals is connected by two rail tracks. Several railcars are available to transport passengers between terminals.

Here now is some of the required behavior, using LSC's. Fig. 1 describes a car departing from a terminal. The objects participating in this scenario are **cruiser**, **car**, **carHandler**. The chart describes the message communication between the objects, with time propagating from top to bottom. The chart of Fig. 1 is universal. Whenever its activation message occurs, i.e., the car receives the message **setDest** from the environment, the sequence of messages in the chart should occur in the following order: the car sends a departure request **departReq** to the car handler, which sends a departure acknowledgment **departAck** back to the car. The car then sends a **start** message to the cruiser in order to activate the engine, and the cruiser responds by sending **started** to the car. Finally, the car sends **engage** to the cruiser and now the car can depart from the terminal.

A scenario in which a car approaches the terminal is described in Fig. 2. This chart is also universal, but here instead of having a single message as an activation, the chart is activated by the prechart shown in the upper part of the figure (in dashed line-style, and looking like a condition, since it is conditional

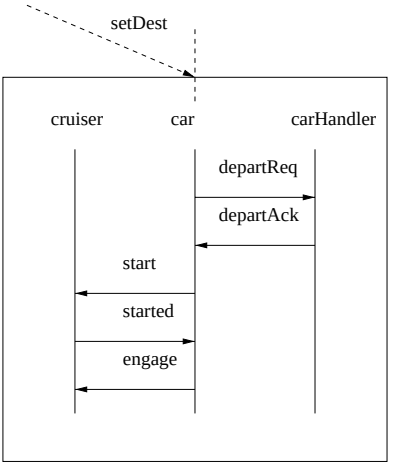


Fig. 1. Perform Departure

in the cold sense of the word — a notion we explain below): in the prechart, the message **departAck** is communicated between the car handler and the car, and the message **alert100** is communicated between the proximity sensor and the car. If these messages indeed occur as specified in the prechart, then the body of the chart must hold: the car sends the arrival request **arrivReq** to the car handler, which sends an arrival acknowledgment **arrivAck** back to the car.

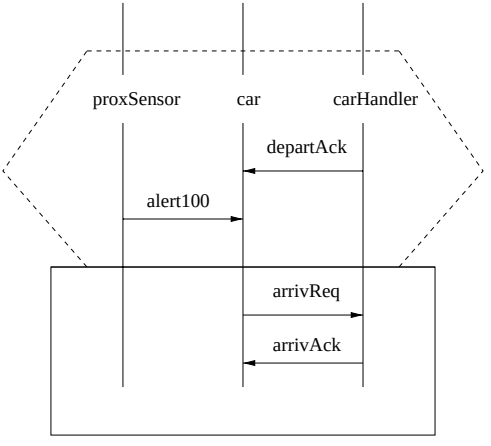


Fig. 2. Perform Approach

Figs. 3 and 4 are existential charts, depicted by dashed borderlines. These charts describe two possible scenarios of a car approaching a terminal: stop at

terminal and pass through terminal, respectively. Since the charts are existential, they need not be satisfied in all runs; it is only required that for each of these charts the system has at least one run satisfying it. In an iterative development of LSC specifications, such existential charts may be considered informal, or underspecified, and can later be transformed into universal charts specifying the exact activation message or prechart that is to determine when each of the possible approaches happens.

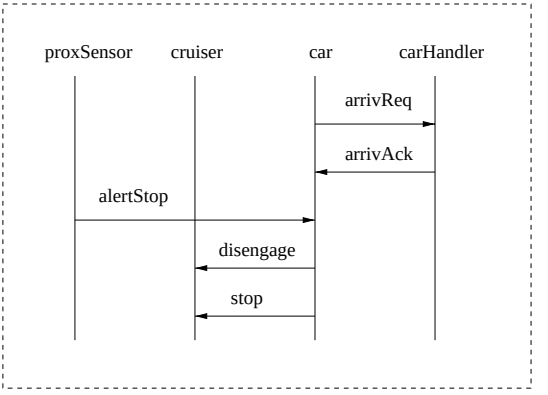


Fig. 3. Stop at terminal

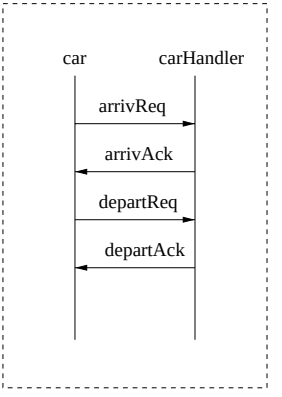


Fig. 4. Pass through terminal

The simple universal chart in Fig. 5 requires that when the proximity sensor receives the message **comingClose** from the environment, signifying that the car is getting close to the terminal, it sends the message **alert100** to the car.

This prevents a system from satisfying the chart in Fig. 2 by never sending the message **alert100** from the proximity sensor to the car, so that the prechart is never satisfied and there is no requirement that the body of the chart hold.

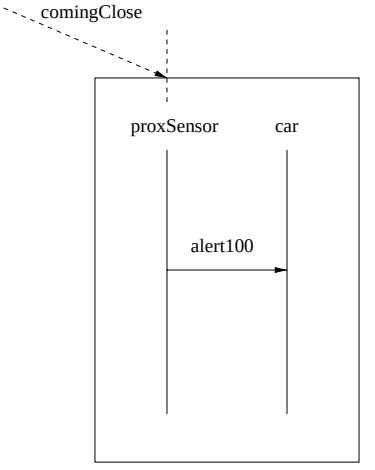


Fig. 5. Coming close to terminal

The set of charts in Figs. 1–5 can be considered as an LSC specification for (part of) the railcar system. Our goal in this paper is to develop algorithms to decide, for any such specification, if there is a satisfying object system and, if so, to synthesize one automatically. As mentioned in the introduction, what makes our goal both harder and more interesting is in the treatment of a set of charts, not just a single one.

3 LSC Semantics

The semantics of the LSC language is defined in [DH99], and we now explain some of the basic definitions and concepts of this semantics using the railcar example.

Consider the **Perform Departure** chart of Fig. 1. In Fig. 6 it appears with a labeling of the **locations** of the chart. The set of locations for this chart is thus:

$$\{\langle cruiser, 0\rangle, \langle cruiser, 1\rangle, \langle cruiser, 2\rangle, \langle cruiser, 3\rangle, \langle car, 0\rangle, \langle car, 1\rangle, \langle car, 2\rangle,$$
$$\langle car, 3\rangle, \langle car, 4\rangle, \langle car, 5\rangle, \langle carHandler, 0\rangle, \langle carHandler, 1\rangle, \langle carHandler, 2\rangle\}$$

The chart defines a partial order $<_m$ on locations. The requirement for order along an instance line implies, for example, $\langle car, 0\rangle <_m \langle car, 1\rangle$. The order induced from message sending implies, for example, $\langle car, 1\rangle <_m \langle carHandler, 1\rangle$. From transitivity we get that $\langle car, 0\rangle <_m \langle carHandler, 1\rangle$.

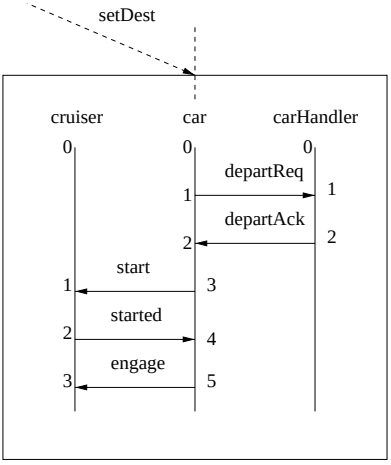


Fig. 6.

One of the basic concepts used for defining the semantics of LSCs, and later on in our synthesis algorithms, is the notion of a **cut**. A cut through a chart represents the progress each instance has made in the scenario. Not every "slice", i.e., a set consisting of one location for each instance, is a cut. For example,

$$(\langle cruiser, 1\rangle, \langle car, 2\rangle, \langle carHandler, 2\rangle)$$

is not a cut. Intuitively the reason for this is that to receive the message **start** by the cruiser (in location $\langle cruiser, 1\rangle$), the message must have been sent, so location $\langle car, 3\rangle$ must have already been reached.

The cuts for the chart of Fig. 7 are thus:

$\{(\langle cruiser, 0\rangle, \langle car, 0\rangle, \langle carHandler, 0\rangle), (\langle cruiser, 0\rangle, \langle car, 1\rangle, \langle carHandler, 0\rangle),$
$(\langle cruiser, 0\rangle, \langle car, 1\rangle, \langle carHandler, 1\rangle), (\langle cruiser, 0\rangle, \langle car, 1\rangle, \langle carHandler, 2\rangle),$
$(\langle cruiser, 0\rangle, \langle car, 2\rangle, \langle carHandler, 2\rangle), (\langle cruiser, 0\rangle, \langle car, 3\rangle, \langle carHandler, 2\rangle),$
$(\langle cruiser, 1\rangle, \langle car, 3\rangle, \langle carHandler, 2\rangle), (\langle cruiser, 2\rangle, \langle car, 3\rangle, \langle carHandler, 2\rangle),$
$(\langle cruiser, 2\rangle, \langle car, 4\rangle, \langle carHandler, 2\rangle), (\langle cruiser, 2\rangle, \langle car, 5\rangle, \langle carHandler, 2\rangle),$
$(\langle cruiser, 3\rangle, \langle car, 5\rangle, \langle carHandler, 2\rangle)\}$

The sequence of cuts in this order constitutes a **run**. The **trace** of this run is:

$(env, car.setDest), (car, carHandler.departReq), (carHandler, car.departAck),$
$(car, cruiser.start), (cruiser, car.started), (car, cruiser.engage)$

This chart has only one run, but in general a chart can have many runs. Consider the chart in Fig. 7. From the initial cut $(0, 0, 0, 0)$ [2] it is possible to

[2] We often omit the names of the objects, for simplicity, when listing cuts.

progress either by the car sending **departReq** to the car handler, or by the passenger sending **pressButton** to the destPanel. Similarly there are possible choices from other cuts. Fig. 8 gives an automaton representation for all the possible runs. This will be the basic idea for the construction of the synthesized state machines in our synthesis algorithms later on. Each state, except for the special starting state s_0, represents a cut and is labeled by the vector of locations. Successor cuts are connected by edges labeled with the message sent. Assuming a synchronous model we do not have separate edges for the sending and receiving of the same message. A path starting from s_0 that returns to s_0 represents a run.

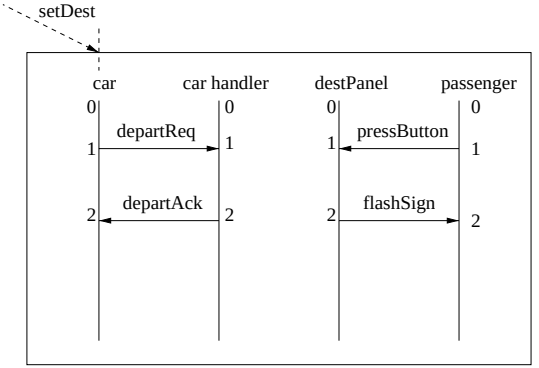


Fig. 7.

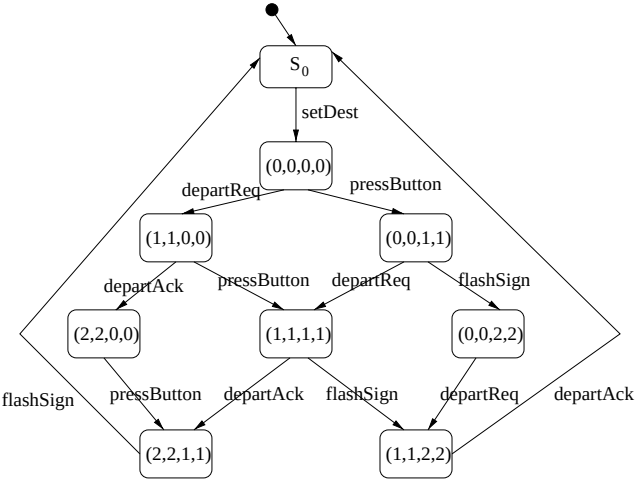


Fig. 8.

Here are two sample traces from these runs:

$(env, car.setDest), (car, carHandler.departReq), (carHandler, car.departAck),$
$(passenger, destPanel.pressButton), (destPanel, passenger.flashSign)$

(env, car.setDest), (car, carHandler.departReq), (passenger, destPanel.pressButton),
(carHandler, car.departAck), (destPanel, passenger.flashSign)

As part of the "liveness" extensions, the LSC language enables forcing progress along an instance line. Each location is given a temperature **hot** or **cold**, graphically denoted by solid or dashed segments of the instance line. A run *must* continue down solid lines, while it *may* continue down dashed lines. Formally, we require that in the final cut in a run all locations are **cold**. Consider the **perform approach** scenario appearing in Fig. 9. The dashed segments in the lower part of the car and carHandler instances specify that it is possible that the message **arrivAck** will not be sent, even in a run in which the prechart holds. This might happen in a situation where the terminal is closed or when all the platforms are full.

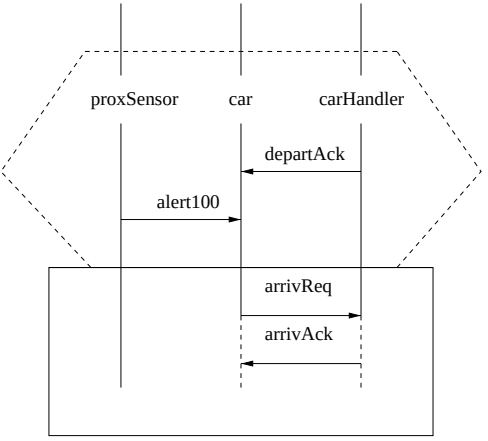


Fig. 9.

When defining the languages of a chart in [DH99], messages that do not appear in the chart are not restricted and are allowed to occur in-between the messages that do appear, without violating the chart. This is an abstraction mechanism that enables concentrating on the relevant messages in a scenario. In practice it may be useful to restrict messages that do not appear explicitly in the chart. Each chart will then have a designated set of messages that are not allowed to occur anywhere except if specified explicitly in the chart; and this applies even

if they do not appear anywhere in the chart. A tool may support convenient selection of this message set. Consider the **perform departure** scenario in Fig. 1. By taking its set of messages to include those appearing therein, but also **alert100**, **arrivReq** and **arrivAck**, we restrict these three messages from occurring during the departure scenario, which makes sense since we cannot arrive to a terminal when we are just in the middle of departing from one.

As in [DH99], an **LSC specification** is defined as:

$$LS = \langle M, amsg, mod \rangle,$$

where M is a set of charts, and $amsg$ and mod are the activation messages[3] and the modes of the charts (existential or universal), respectively.

A system **satisfies** an LSC specification if, for every universal chart and every run, whenever the activation message holds the run must satisfy the chart, and if, for every existential chart, there is at least one run in which the activation message holds and then the chart is satisfied. Formally,

Definition 1. *A system S* **satisfies** *the LSC specification $LS = \langle M, amsg, mod \rangle$, written $S \models LS$, if:*

1. $\forall m \in M, \quad mod(m) = universal \Rightarrow \forall \eta \; \mathcal{L}_S^\eta \subseteq \mathcal{L}_m$
2. $\forall m \in M, \quad mod(m) = existential \Rightarrow \exists \eta \; \mathcal{L}_S^\eta \cap \mathcal{L}_m \neq \emptyset$

Here $\mathcal{L}_S^\eta$ is the trace set of object system S on the sequence of directed requests η. We omit a detailed definition here, which can be found, e.g., in [HKp99]. $\mathcal{L}_m$ is the language of the chart m, containing all traces satisfying the chart. We say that an LSC specification is **satisfiable** if there is a system that satisfies it.

4 Consistency of LSCs

Our goal is to automatically construct an object system that is correct with respect to a given LSC specification. When working with an expressive language like LSCs that enables specifying both necessary and forbidden behavior, and in which a specification is a well-defined set of charts of different kinds, there might very well be self contradictions, so that there might be no object system that satisfies it.

Consider an LSC specification that contains the universal charts of Figs. 10 and 11. The message **setDest** sent from the environment to the car activates Fig. 10, which requires that following the **departReq** message, **departAck** is sent from the car handler to the car. This message activates Fig. 11, which requires the sending of **engage** from the car to the cruiser before the **start** and **started** messages are sent, while Fig. 10 requires the opposite ordering. A contradiction.

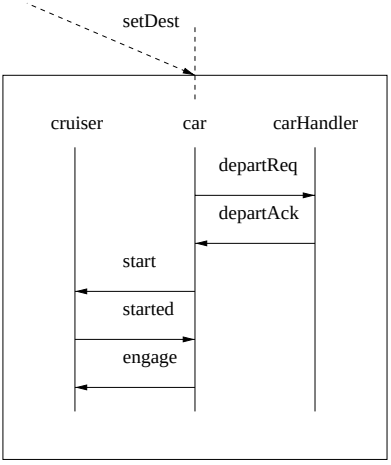


Fig. 10.

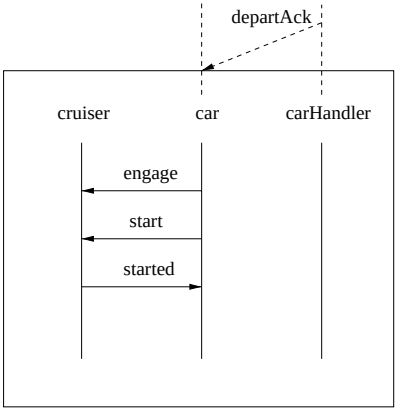


Fig. 11.

This is only a simple example of an inconsistency in an LSC specification. Inconsistencies can be caused by such an "interaction" between more than two universal charts, and also when a scenario described in an existential chart can never occur because of the restrictions from the universal charts. In a complicated system consisting of many charts the task of finding such inconsistencies manually by the developers can be formidable, and algorithmic support for this process can help in overcoming major problems in early stages of the analysis.

[3] In the general case we allow a prechart instead of only a single activation message. However, in this paper we provide the proofs of our results for activation messages, but they can be generalized rather easily to precharts too.

4.1 Consistency = Satisfiability

We now provide a global notion of the consistency of an LSC specification. This is easy to do for conventional, existential MSCs, but is harder for LSCs. In particular, we have to make sure that a universal chart is satisfied by *all* runs, from *all* points in time.

We will use the following notation: A_{in} is the alphabet denoting messages sent from the environment to objects in the system, while A_{out} denotes messages sent between the objects in the system.

Definition 2. *An LSC specification* $LS = \langle M, amsg, mod \rangle$ *is* **consistent** *if there exists a nonempty regular language* $\mathcal{L}_1 \subseteq (A_{in} \cdot A_{out}^*)^*$ *satisfying the following properties:*

1. $\mathcal{L}_1 \subseteq \bigcap_{m_j \in M,\ mod(m_j)=universal} \mathcal{L}_{m_j}$
2. $\forall w \in \mathcal{L}_1\ \forall a \in A_{in}\ \exists r \in A_{out}^*,\ \ s.t.\ \ w \cdot a \cdot r \in \mathcal{L}_1.$
3. $\forall w \in \mathcal{L}_1,\ w = x \cdot y \cdot z,\ y \in A_{in} \Rightarrow x \in \mathcal{L}_1.$
4. $\forall m \in M,\ mod(m) = existential \Rightarrow \mathcal{L}_m \cap \mathcal{L}_1 \neq \emptyset.$

The language $\mathcal{L}_1$ is what we require as the set of satisfying traces. Clause 1 in the definition requires all universal charts to be satisfied by all the traces in $\mathcal{L}_1$, Clause 2 requires a trace to be extendible if a new message is sent in from the environment, Clause 3 essentially requires traces to be completed before new messages from the environment are dealt with, and Clause 4 requires existential charts to be satisfied by traces from within $\mathcal{L}_1$.

Now comes the first central result of the paper, showing that the consistency of an LSC specification is a necessary and sufficient condition for the existence of an object system satisfying it.

Theorem 1. *A specification LS is satisfiable if and only if it is consistent.*

Proof. Appears in the Appendix.

A basic concept used in the proof of Theorem 1 is the notion of a **global system automaton**, or a **GSA**. A GSA describes the behavior of the entire system — the message communication between the objects in the system in response to messages received from the environment. A rigorous definition of the GSA appears in the appendix. Basically, it is a finite state automaton with input alphabet consisting of messages sent from the environment to the system (A_{in}), and output alphabet consisting of messages communicated between the objects in the system (A_{out}). The GSA may have **null transitions**, transitions that can be taken spontaneously without the triggering of a message. We add a **fairness requirement**: a null transition that is enabled an infinite number of times must be taken an infinite number of times. A *fair cycle* is a loop of states connected by null transitions, which can be taken repeatedly without violating

the fairness requirement. We require that the system has no fair cycles, thus ensuring that the system's reactions are finite.

In the proof of Theorem 1 (the *Consistency* $\Rightarrow$ *Satisfiability* direction in the Appendix) we show that it is possible to construct a GSA satisfying the specification. This implies the existence of an object system (a separate automaton for each object) satisfying the specification. Later on, when discussing synthesis, we will show methods for the distribution of the GSA between the objects to obtain a satisfying object system. In section 5.5 we show that the fairness requirement is not essential for our construction — it is possible to synthesize a satisfying object system that does not use null transition and the fairness requirement, although it does not generate the most general language.

4.2 Deciding Consistency

It follows from Theorem 1 that to prove the existence of an object system satisfying an LSC specification LS, it suffices to prove that LS is consistent. In this section we present an algorithm for deciding consistency.

A basic construction used in the algorithm is that of a deterministic finite automaton accepting the language of a universal chart. Such an automaton for the chart of Fig. 7 is shown in Fig. 12. The initial state s_0 is the only accepting state. The activation message **setDest** causes a transition from state s_0, and the automaton will return to s_0 only if the messages **departReq, departAck, pressButton** and **flashSign** occur as specified in the chart. Notice that the different orderings of these messages that are allowed by the chart are represented in the automaton by different paths. Each such message causes a transition to a state representing a successor cut. The self transitions of the nonaccepting states allow only messages that are not restricted by the chart. The initial state s_0 has self transitions for message **comingClose** sent from the environment and for all other messages between objects in the system. To avoid cluttering the figure we have not written the messages on the self transitions.

The construction algorithm of this automaton and its proof of correctness are omitted from this version of the paper.

An automaton accepting exactly the runs that satisfy *all* the universal charts can be constructed by intersecting these separate automata. This intersection automaton will be used in the algorithm for deciding consistency. The idea is to start with this automaton, which represents the "largest" regular language satisfying all the universal charts, and to systematically narrow it down in order to avoid states from which the system will be forced by the environment to violate the specification. At the end we must check that there are still representative runs satisfying each of the existential charts.

Here, now is our algorithm for checking consistency:

Algorithm 2 *1. Find the minimal DFA* $\mathcal{A} = (A, S, s_0, \rho, F)$ *that accepts the language*

$$\mathcal{L} = \bigcap_{m_j \in M,\ mod(m_j)=universal} \mathcal{L}_{m_j}$$

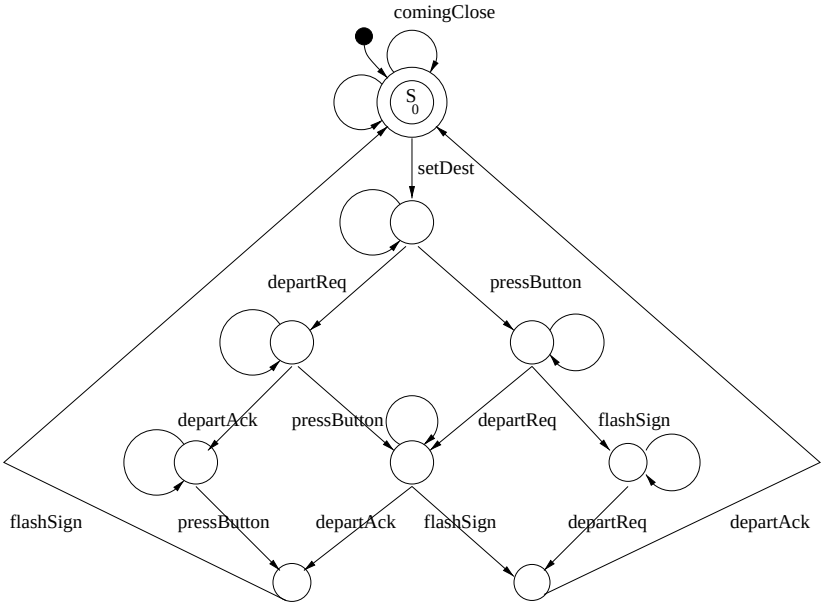


Fig. 12.

(The existence of such an automaton follows from the discussion above and is proved in the full version of the paper [HKg99].)

2. *Define the sets* $Bad_i \subseteq S$, *for* $i = 0, 1, ...,$ *as follows:*
   $Bad_0 = \{s \in S \mid \exists a \in A_{in},\ s.t.\ \forall x \in A^*_{out}\ \rho(s, a \cdot x) \notin F\}$,
   $Bad_i = \{s \in S \mid \exists a \in A_{in},\ s.t.\ \forall x \in A^*_{out}\ \rho(s, a \cdot x) \notin F - Bad_{i-1}\}$.
   The series Bad_i *is monotonically increasing, with* $Bad_i \subseteq Bad_{i+1}$, *and since* S *is finite it converges. Let us denote the limit set by* Bad_{max}.
3. *From* $\mathcal{A}$ *define a new automaton* $\mathcal{A}' = (A, S, s_0, \rho, F')$, *where the set of accepting states has been reduced to* $F' = F - Bad_{max}$
4. *Further reduce* $\mathcal{A}$, *by removing all transitions that lead from states in* $S - F'$, *and which are labeled with elements of* A_{in}. *This yields the new automaton* $\mathcal{A}''$.
5. *Check whether* $\mathcal{L}(\mathcal{A}'') \neq \emptyset$ *and whether, in addition,* $\mathcal{L}_{m_i} \cap \mathcal{L}(\mathcal{A}'') \neq \emptyset$ *for each* $m_i \in M$ *with* $mod(m_i) = existential$. *If both are true output* YES*; otherwise output* NO.

Proposition 1. *The algorithm is correct: given a specification LS, it terminates and outputs* YES *iff LS is consistent.*

Proof. Omitted in this version of the paper. See [HKg99].

In case the algorithm answers YES, the specification is consistent and it is possible to proceed to automatically synthesize the system, as we show in the

next section. However, for the cases where the algorithm answers NO, it would be very helpful to provide the developer with information about the source of the inconsistency. Step 5 of our algorithm provides the basis for achieving this goal. Here is how.

The answer is NO if $\mathcal{L}(\mathcal{A}'') = \emptyset$ or if there is an existential chart m_i such that $\mathcal{L}_{m_i} \cap \mathcal{L}(\mathcal{A}'') = \emptyset$. In the second case, this existential chart is the information we need. The first case is more delicate: there is a sequence of messages sent from the environment to the system (possibly depending on the reactions of the system) that eventually causes the system to violate the specification. Unlike verification against a specification, where we are given a specific program or system and can display a specific run of it as a counter-example, here we want to **synthesize** the object system so we do not yet have any concrete runs. A possible solution is to let the supporting tool play the environment and the user play the system, with the aim of locating the inconsistency. The tool can display the charts graphically and highlight the messages sent and the progress made in the different charts. After each message sent by the environment (determined by the tool using the information obtained in the consistency algorithm), the user decides which messages are sent between the objects in the system. The tool can suggest a possible reaction of the system, and allow the user to modify it or choose a different one. Eventually, a universal chart will be violated, and the chart and the exact location of this violation can be displayed.

5 Synthesis of FSMs from LSCs

We now show how to automatically synthesize a satisfying object system from a given consistent specification. We first use the algorithm for deciding consistency (Algorithm 2), relying on the equivalence of consistency and satisfiability (Theorem 1) to derive a global system automaton, a GSA, satisfying the specification. Synthesis then proceeds by distributing this automaton between the objects, creating a desired object system.

The synthesis is demonstrated on our example, taking the charts in Figs. 1–5 to be the required LSC specification. For the universal charts, Figs. 1, 2 and 5, we assume that the sets of restricted messages (those not appearing in the charts) are { **alertStop**, **alert100**, **arrivReq**, **arrivAck**, **disengage**, **stop** }, { **departReq**, **start**, **started**, **engage** } and { **departAck**}, respectively.

Figs. 13, 14 and 15 show the automata for the **perform departure**, **perform approach** and **coming close** charts, respectively. Notice that in Fig. 14 there are two accepting states s_0 and s_1, since we have a prechart with messages **departAck** and **alert100** that causes activation of the body of the chart. To avoid cluttering the figures we have not written the messages on the self transitions. For nonaccepting states these messages are the non-restricted messages between objects in the system, while for accepting states we take all messages that do not cause a transition from the state, including messages sent by the environment.

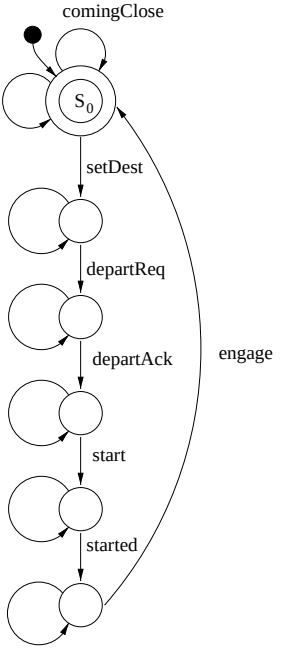


Fig. 13. Automaton for Perform Departure

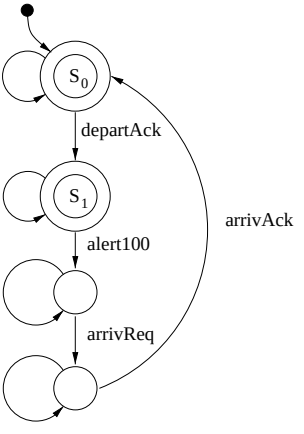


Fig. 14. Automaton for Perform Approach

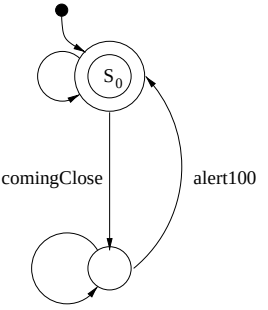


Fig. 15. Automaton for Coming Close

The intersection of the three automata of Figs. 13, 14 and 15 is shown in Fig. 16. It accepts all the runs that satisfy all three universal charts of our system.

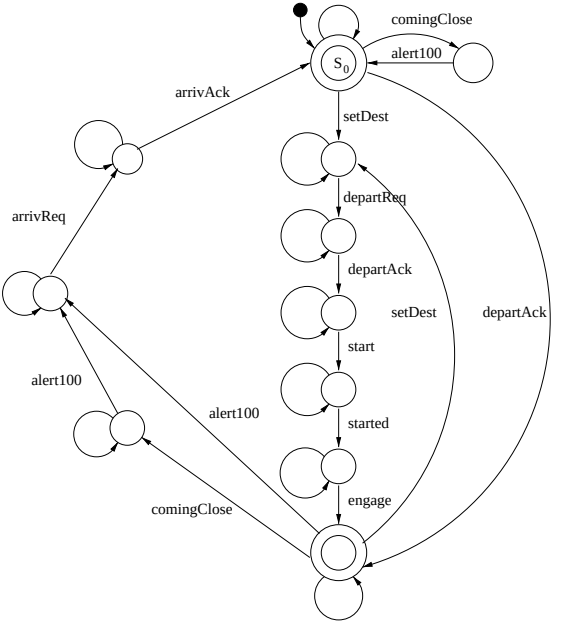


Fig. 16. The Intersection Automaton

The global system automaton (GSA) derived from this intersection automaton is shown in Fig. 17. The two accepting states have as outgoing transitions only messages from the environment. This has been achieved using the techniques described in the proof of Theorem 1 (see the Appendix). Notice also the

existence of runs satisfying each of the existential charts. We have used the path extraction methods of Section 5.5 to retain these runs.

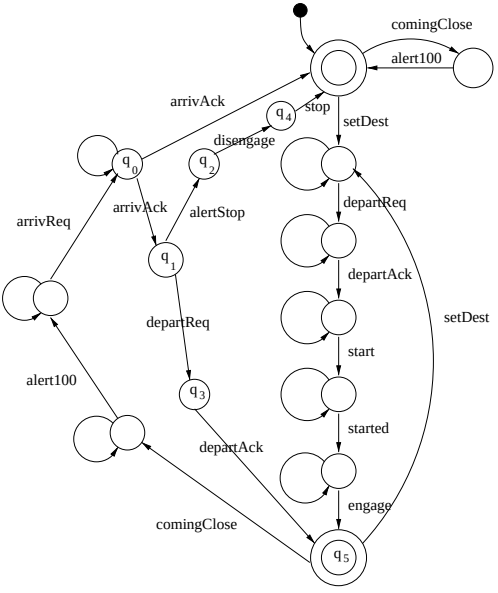


Fig. 17. The Global System Automaton

After constructing the GSA, the synthesis proceeds by distributing the automaton between the objects, creating a desired object system. To illustrate the distribution we focus on a subautomaton of the GSA consisting of the states q_0, q_1, q_2, q_3, q_4 and q_5, as appearing in Fig. 17. This subautomaton is shown in Fig. 18. In this figure we provide full information about the message, the sender and receiver, since this information is important for the distribution process.

In general, let $A = \langle Q, q_0, \delta \rangle$ be a GSA describing a system with objects $\mathcal{O} = \{O_1, ..., O_n\}$ and messages $\Sigma = \Sigma_{in} \cup \Sigma_{out}$. Assume that A satisfies the LSC specification LS. Our constructions employ new messages taken from a set Σ_{col}, where $\Sigma_{col} \cap \Sigma = \emptyset$. They will be used by the objects for collaboration in order to satisfy the specification, and are not restricted by the charts in LS.

There are different ways to distribute the global system automaton between the objects. In the next three subsections we discuss three main approaches — **controller object**, **full duplication**, and **partial duplication** — and illustrate them on the GSA subautomaton of Fig. 18. The first approach is trivial and is shown essentially just to complete the proof of the existence of an object system satisfying a consistent specification. The second method is an intermediate stage towards the third approach, which is more realistic.

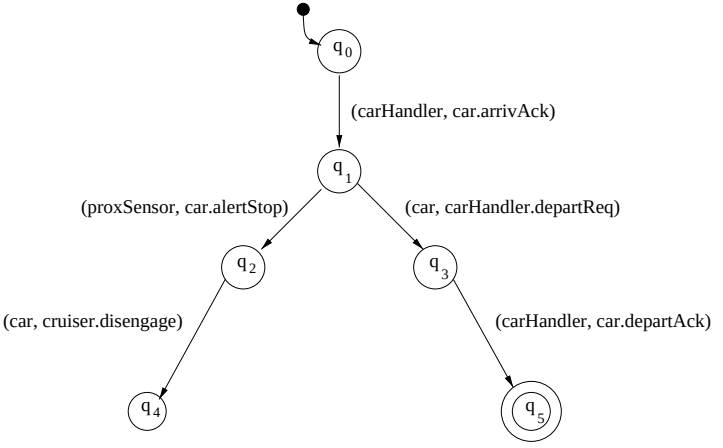


Fig. 18. Subautomaton of the GSA

5.1 Controller Object

In this approach we add to the set of objects in the system $\mathcal{O}$ an additional object O_{con} which acts as the controller of the system, sending commands to all the other objects. These will have simple automata to enable them to carry out the commands.

Let $|\Sigma_{col}| = |A_{in}| + |A_{out}|$, and let f be a one-to-one function

$$f : A_{in} \cup A_{out} \to \Sigma_{col}$$

We define the state machine of the controller object O_{con} to be $\langle Q, q_0, \delta_{con} \rangle$, and the state machines of object $O_i \in \mathcal{O}$ to be $\langle \{q_{O_i}\}, q_{O_i}, \delta_{O_i} \rangle$.

The states and the initial state of O_{con} are identical to those of the GSA. The transition relation δ_{con} and the transition relations δ_{O_i} are defined as follows:

If $(q, a, q') \in \delta$ where $a \in A_{in}$, $a = (env, O_i.\sigma_i)$ then

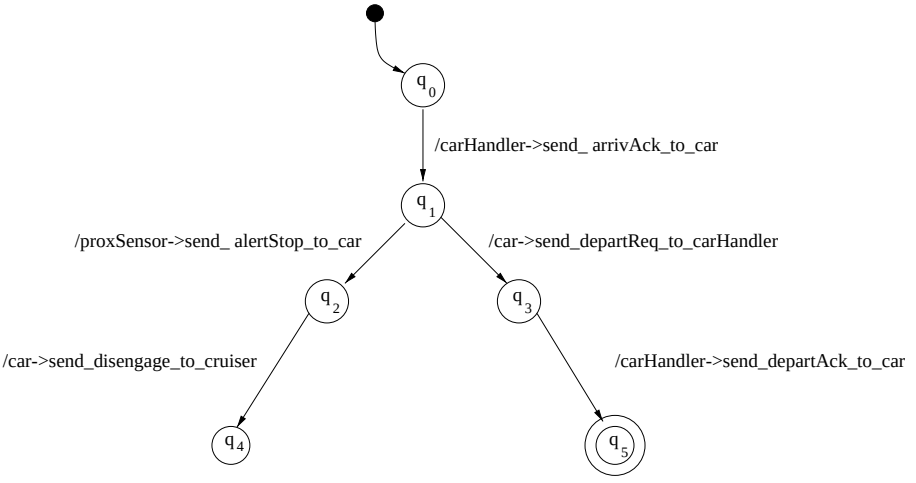
$$(q, f(a), q') \in \delta_{con} \quad \text{and} \quad (q_{O_i}, \sigma_i / O_{con}.f(a), q_{O_i}) \in \delta_{O_i}.$$

If $(q, /a, q') \in \delta$ where $a \in A_{out}$, $a = (O_i, O_j.\sigma_j)$ then

$$(q, /O_i.f(a), q') \in \delta_{con} \quad \text{and} \quad (q_{O_i}, f(a)/O_j.\sigma_j, q_{O_i}) \in \delta_{O^i}.$$

This construction is illustrated in Fig. 19, which shows the object system obtained by the synthesis from the GSA of Fig. 18. It includes the state machine of the controller object O_{con}, and the transitions of the single-state state machines of the objects **carHandler**, **car** and **proxSensor**.

The size of the state machine of the controller object O_{con} is equal to that of the GSA, while all other objects have state machines with one state. Section 5.4 discusses the total complexity of the construction.



carHandler:	send_arrivAck_to_car/car->arrivAck send_departAck_to_car/car->departAck
car:	send_departReq_to_carHandler/carHandler->departReq send_disengage_to_cruiser/cruiser->disengage setDest/control->car_got_setDest
proxSensor:	send_alertStop_to_car/car->alertStop comingClose/control->proxSensor_got_comingClose

Fig. 19. Controller

5.2 Full Duplication

In this construction there is no controller object. Instead, each object will have the state structure of the GSA, and will thus "know" what state the GSA would have been in.

Recalling that $A = \langle Q, q_0, \delta \rangle$ is the GSA, let k be the maximum outdegree of the states in Q. A labeling of the transitions of A is a one-to-one function tn:

$$tn : \delta \to \{1, ..., k\}$$

Let $|\Sigma_{col}| = k$ and let f be a one-to-one function

$$f : \{1, ..., k\} \to \Sigma_{col}$$

The state machine for object O_i in $\mathcal{O}$ is defined to be $\langle Q, q_0, \delta_{O_i} \rangle$.
If $(q, a, q') \in \delta$, where $a \in A_{in}$, $a = (env, O_i.\sigma_i)$ and $a' = f(tn(q, a, q')) \in \Sigma_{col}$, then $(q, \sigma_i / O_{i+1}.a') \in \delta_{O_i}$ and for every $j \neq i$, $(q, a'/O_{j+1}.a', q') \in \delta_{O_j}$.
If $(q, /a, q') \in \delta$, where $a \in A_{out}$, $a = (O_i, O_j.\sigma_j)$ and $a' = f(tn(q, /a, q')) \in \Sigma_{col}$, then $(q, /O_j.\sigma_j; O_{i+1}.a', q') \in \delta_{O_i}$ and for every $j \neq i$, $(q, a'/O_{j+1}.a', q') \in \delta_{O_j}$.

This construction is illustrated in Fig. 20 on the sub-GSA of Fig. 18. The maximal outdegree of the states of the GSA in this example is 2, and the set of

collaboration messages is $\Sigma_{col} = \{1, 2\}$. Again, complexity is discussed in Section 5.4.

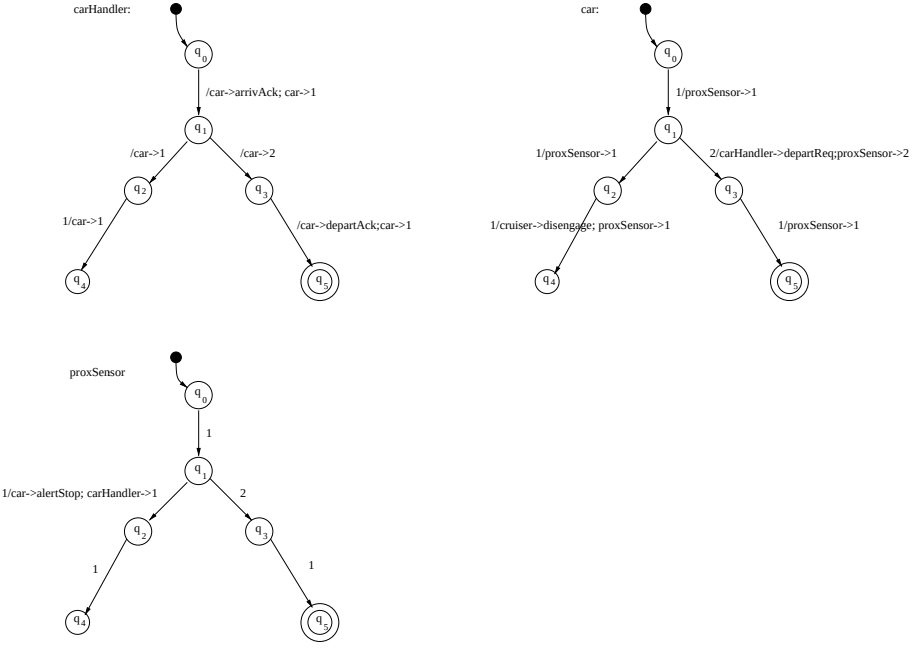


Fig. 20. Full Duplication

5.3 Partial Duplication

The idea here is to distribute the GSA as in the full duplication construction, but to merge states that carry information that is not relevant to this object in question. In some cases this can reduce the total size, although the worst case complexity remains the same.

The state machine of object O_i is defined to be $\langle Q_{O_i} \cup q_{idle}, q_0, \delta_{O_i} \rangle$, where $Q_{O_i} \subseteq Q$ is defined by

$$Q_{O_i} = \left\{ q \in Q \;\middle|\; \begin{array}{l} \exists q' \in Q \; \exists a \in A_{out} \text{ s.t.} \\ a = (O_i, O_j.\sigma_j), (q, /a, q') \in \delta \text{ or} \\ \exists q' \in Q \; \exists a \in A_{in} \text{ s.t.} \\ a = (env, O_i.\sigma_i), (q', a, q) \in \delta \end{array} \right\}$$

Thus, in object O_i we keep the states that the GSA enters after receiving a message from the environment, and the states from which O_i sends messages.

Let $|\Sigma_{col}| = |Q|$, and let f be a one-to-one function

$$f : Q \to \Sigma_{col}$$

The transition relation δ_{O_i} for object O_i is defined as follows:
If $(q, a, q') \in \delta$, $a = (env, O_i.\sigma_i)$ then $(q, \sigma_i / O_{i+1}.f(q'), q') \in \delta_{O_i}$.
If $(q, /a, q') \in \delta$, $a = (O_j, O_i.\sigma_i)$, then
either $q' \in Q_{O_j}$ and then $(q, /O_i.\sigma_i; O_{j+1}.f(q'), q') \in \delta_{O_j}$,
or $q' \notin Q_{O_j}$ and then $(q, /O_i.\sigma_i; O_{j+1}.f(q'), q_{idle}) \in \delta_{O_j}$.
If $q \in Q_{O_i}$, $q' \in Q_{O_i}$ then $(q, f(q'), q') \in \delta_{O_i}$.
If $q \in Q_{O_i}$, $q' \notin Q_{O_i}$ then $(q, f(q'), q_{idle}) \in \delta_{O_i}$.
For every $q \in Q_{O_i}$, $(q_{idle}, f(q), q) \in \delta_{O_i}$.

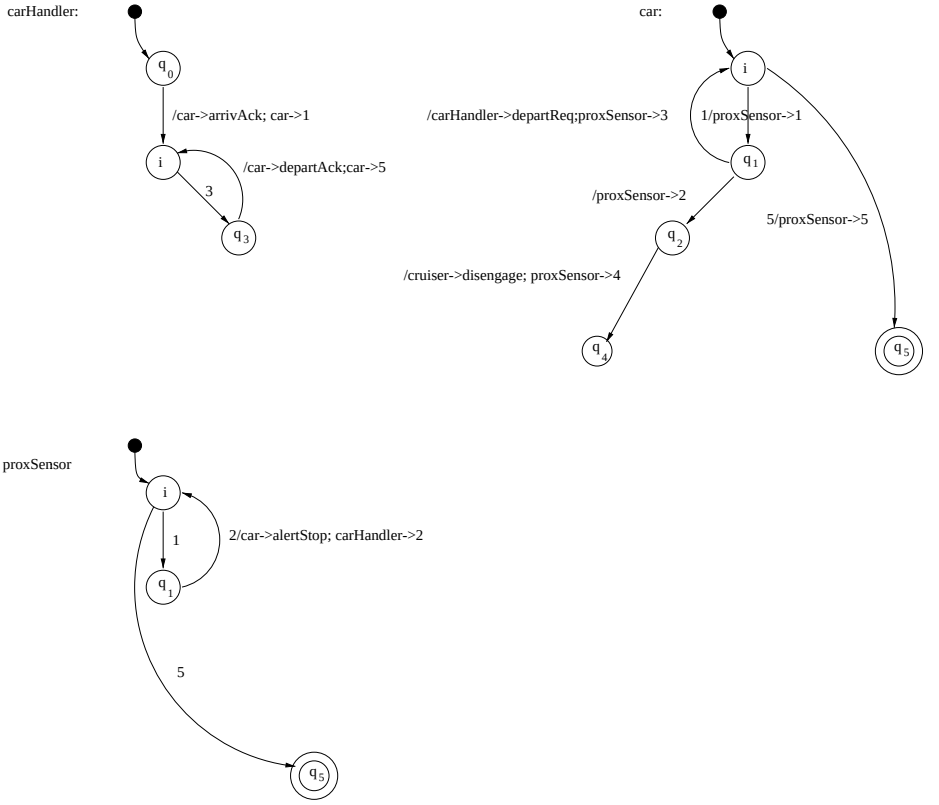


Fig. 21. Partial Duplication

This construction is illustrated in Fig. 21. The states of the GSA of Fig. 18 that were eliminated are q_1, q_2, q_4 and q_5 for **carHandler**, q_0 and q_3 for **car** and q_0, q_2, q_3 and q_4 for **proxSensor**.

5.4 Complexity Issues

In the previous sections we showed how to distribute the satisfying GSA between the objects, to create an object system satifying the LSC specification LS. We now discuss the size of the resulting system, relative to that of LS.

We take the size of an LSC chart m to be

$$|m| = |dom(m)| = |\#\text{ of locations in } m|,$$

and the size of an LSC specification $LS = \langle M, amsg, mod \rangle$ to be

$$|LS| = \sum_{m \in M} |m|.$$

The size of the GSA $A = \langle Q, q_0, \delta \rangle$ is simply the number of states $|Q|$. We ignore the size of the transition function δ which is polynomial in the number of states $|Q|$. Similarly, the size of an object is the number of states in its state machine.

Let LS be a consistent specification, where the universal charts in M are $\{m_1, m_2, ..., m_t\}$. Let A be the satisfying GSA derived using the algorithm for deciding consistency (Algorithm 2). A was obtained by intersecting the automata $A_1, A_2, ..., A_t$ that accept the runs of charts $m_1, m_2, ..., m_t$, respectively, and then performing additional transformations that do not change the number of states in A. The states of automaton A_i correspond to the cuts through chart m_i, as illustrated, for example, in Fig. 9.

Proposition 2. *The number of cuts through a chart m with n instances is bounded by $|m|^n$.*

Proof. Omitted in this version of the paper.

This is consistent with the estimate given in [AY99] for their analysis of the complexity of model checking for MSCs. We now estimate the size of the GSA.

Proposition 3. *The size of the GSA automaton A constructed in the proof of Theorem 1 satisfies*

$$|A| \quad \leq \quad \prod_{i=1}^{t} |m_i|^{n_i} \quad \leq \quad |LS|^{nt},$$

where n_i is the number of instances appearing in chart m_i, n is the total number of instances appearing in LS, and t is the number of universal charts in LS.

Proof. Omitted in this version of the paper.

The size of the GSA A is thus polynomial in the size of the specification LS, if we are willing to treat the number of objects in the system and the number of charts in the specification as constants. In some cases a more realistic assumption would be to fix one of these two, in which case the synthesized

automaton would be exponential in the remaining one. The time complexity of the synthesis algorithm is polynomial in the size of A.

The size of the synthesized object system is determined by the size of the GSA A. In the controller object approach (Section 5.1), the controller object is of size $|A|$ and each of the other objects is of constant size (one state). In the full duplication approach (Section 5.2), each of the objects is of size $|A|$, while in the partial duplication approach (Section 5.3), the size of each of the objects can be smaller than $|A|$, but the total size of the system is at least $|A|$.

5.5 Synthesis without Fairness Assumptions

We have shown that for a consistent specification we can find a GSA and then construct an object system that satisfies the specification. This construction used null transitions and a fairness assumption related to them, i.e., that a null transition that is enabled an infinite number of times is taken an infinite number of times. We now show that consistent specifications also have satisfying object systems with no null transitions.

Let $A = \langle Q, q_0, \delta \rangle$ be the GSA satisfying the specification LS, derived using the algorithm for deciding consistency. We partition Q into two sets: Q_{stable}, the states in Q that do not have outgoing null transitions, and $Q_{transient}$, the states of which all the outgoing transitions are null transitions. Such a partition is possible, as implied by the proof of Theorem 1. Now, A may have a loop of null transitions consisting of states in $Q_{transient}$. Such a loop represents an infinite number of paths and it will not be possible to maintain all of them in a GSA without null transitions. To overcome this, we create a new GSA $A' = \langle Q', q_0, \delta' \rangle$, with $Q' \subseteq Q$ and $\delta' \subseteq \delta$, as follows.

Let $m \in M$ be an existential chart, $mod(m) = existential$. A satisfies the specification LS, so there exists a word w, with $w \in \mathcal{L}_A \cap \mathcal{L}_m$. Let $q^0, q^1, ...$ be the sequence of states that A goes through when generating w, and let $\delta^0, \delta^1 ...$ be the transitions taken. Since $w \in \mathcal{L}_m$, let $i_1, ..., i_k$, such that $w_{i_1} \cdot w_{i_2} \cdots w_{i_k} \in \mathcal{L}_m^{trc}$. Let j be the minimal index such that $j > i_k$ and $q^j \in Q_{stable}$. The new GSA A' will retain all the states that appear in the sequence $q^0, ..., q^j$ and all the transitions that were used in $\delta^0, ..., \delta^j$. This is done for every existential chart $m \in M$.

In addition, for every $q_i, q_j \in Q$ and for every $a \in A_{in}$, if there exists a sequence of states $q_i, q^1, ..., q^l, q_j$ such that $(q_i, a, q^1) \in \delta$ and for every $1 \leq k < l$ there is a null transition $\delta^k \in \delta$ between q^k and q^{k+1}, then for one such sequence we keep in A' the states $q^1, ..., q^k$ and the transitions $\delta^1, ..., \delta^k$.

All other states and transition of A are eliminated in going from A to A'.

Proposition 4. *The GSA A' satisfies the specification LS.*

Proof. Omitted in this version of the paper.

6 Synthesizing Statecharts

We now outline an approach for a synthesis algorithm that uses the main succinctness feature of statecharts [H87] (see also [HG97]), namely, concurrency, via orthogonal states.

Consider a consistent specification $LS = \langle M, amsg, mod \rangle$, where the universal charts in M are $M_{universal} = \{m_1, m_2, ..., m_t\}$. In the synthesized object system each object O_i will have a top-level AND state with t orthogonal component OR states, $s_1, s_2, ..., s_t$. Each s_j has substates corresponding to the locations of object O_i in chart m_j.

Assume that in a scenario described by one of the charts in $M_{universal}$, object O_i has to send message σ to object O_j. If object O_i is in a state describing a location just before this sending, O_i will check whether O_j is in a state corresponding to the right location, and is ready to receive. (This can be done using one of the mechanisms of statecharts for sensing another object's state.) The message σ can then be sent and the transition taken. All the other component states of O_i and O_j will synchronously take the corresponding transitions if necessary.

This was a description of the local check that an object has to perform before sending a message and advancing to the next location for one chart. Actually, the story is more complicated, since when advancing in one chart we must check that this does not contradict anything in any of the other charts. Even more significantly, we also must check that taking the transition will not get the system into a situation in which it will not be able to satisfy one of the universal charts.

To deal with these issues the synthesis algorithm will have to figure out which state configurations should be avoided. Specifically, let c_i be a cut through chart m_i. We say that $C = (c_1, c_2, ..., c_t)$ is a **supercut** if for every i, c_i is a cut through m_i. We say that supercut $C' = (c'_1, c'_2, ..., c'_t)$ is a **successor** of supercut $C = (c_1, c_2, ..., c_t)$, if there exists i with $succ_{m_i}(c_i, (j, l_j), c'_i)$ and such that for all $k \neq i$ the cut c'_k is consistent with communicating the message $msg(j, l_j)$ while in cut c_k.
Now, for $i = 0, 1, ...$, define the sets

$Bad_i \subseteq \{$all supercuts s.t. at least one of the cuts has at least one hot location$\}$

as follows:

$$Bad_0 = \{C \mid C \text{ has no successors } \}$$

$$Bad_i = \{C | C \in Bad_{i-1} \text{ or all successors of } C \text{ are in } Bad_{i-1}\}$$

The series Bad_i is monotonically increasing under set inclusion, so that $Bad_i \subseteq Bad_{i+1}$. Since the set of all supercuts is finite the series converges. Denote its limit by Bad_{max}. The point now is that before taking a transition the synthesized object system will have to check that it does not lead to a supercut in Bad_{max}.

The construction is illustrated in Figs. 22, 23, 24 and 25 which show the statecharts for car, carHandler, proxSensor and cruiser, respectively, obtained

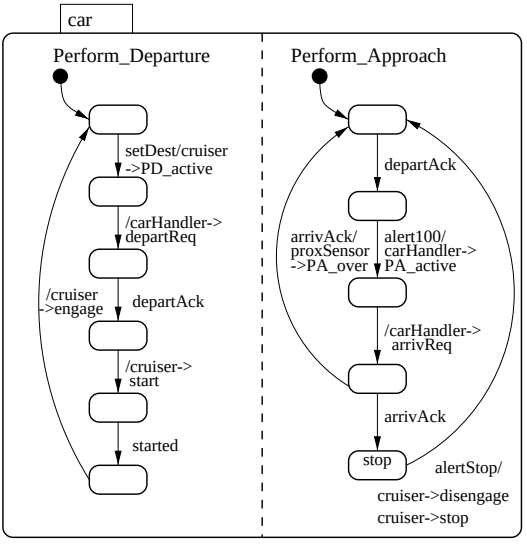


Fig. 22. Statechart of car

from the railcar system specification. Notice that an object that does not actively participate in some universal chart, does not need a component in its statechart for this scenario, for example proxSensor does not have a **Perform Departure** component. Notice the use of the *in* predicate in the statechart of the proxSensor for sensing if the car is in the **stop** state.

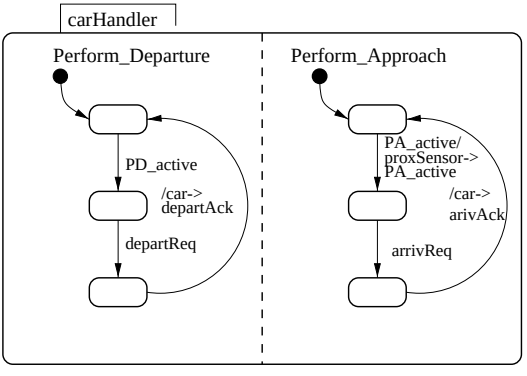


Fig. 23. Statechart of carHandler

The number of states in this kind of synthesized statechart-based system is on the order of the total number of locations in the charts of the specification. Now, although in the GSA solution the number of states was exponential in the number

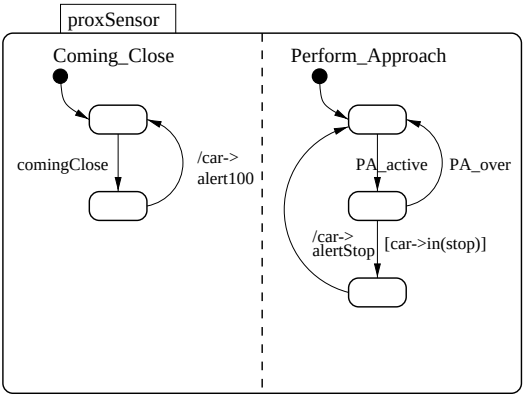


Fig. 24. Statechart of proxSensor

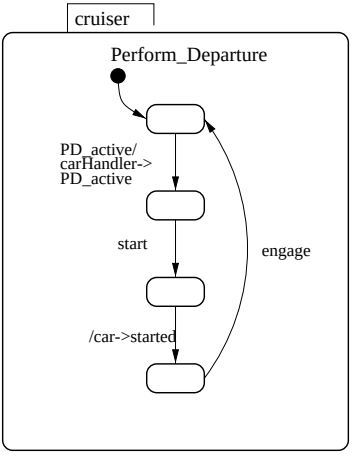


Fig. 25. Statechart of cruiser

of universal charts and in the number of objects in the system, which seems to contrast sharply with the situation here, the comparison is misleading; the guards of the transitions here may involve lengthy conditions on the states of the system. In practice, it may prove useful to use OBDD's for efficient representation and manipulation of conditions over the system state space.

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APPENDIX: Proof of Theorem 1

Proof. The proof relies on the definitions of an object system appearing in [HKp99], somewhat modified. In [HKp99] a basic computational model for object-oriented designs is presented. It defines the behavior of systems composed of instances of object classes, whose behavior is given by conventional state machines. In our work we assume a single instance of each class during the entire evolution of the system — we do not deal with dynamic creation and destruction of instances. We assume all messages are synchronous and that there are no failures in the system — every message that is sent is received.

($\Rightarrow$) Let the object system S be such that $S \models LS$. We let $\mathcal{L}_S = \cup_{\eta \in A_{in}^*} \mathcal{L}_S^\eta$, and show that $\mathcal{L}_S$ satisfies the four requirements of $\mathcal{L}_1$ in the definition of a consistent specification, Def. 2.

(1) From the definition of an object system it follows that $\mathcal{L}_S$ is regular and nonempty. The system S satisfies the specification LS. Hence, if we set $\mathcal{L} = \bigcap_{m_j \in M, mod(m_j)=universal} \mathcal{L}_{m_j}$, Clause 1 of the definition of satisfaction (Def. 1) implies $\forall \eta\ \mathcal{L}_S^\eta \subseteq \mathcal{L}$. Thus, $\mathcal{L}_S = \cup_\eta \mathcal{L}_S^\eta \subseteq \mathcal{L}$.

(2 and 3) Let $w \in \mathcal{L}_S$. There exists a sequence of directed requests sent by the environment, $\eta = O^0.\sigma^0 \cdot O^1.\sigma^1 \cdots O^n.\sigma^n$, such that w is the behavior of the system S while reacting to the sequence of requests η. Now, w belongs to the trace set of S on η, so that $w = w_0 \cdot w_1 \cdots w_n$, $w_i \in A^*$, $first(w_i) = (env, O^i.\sigma^i)$, and there exists a sequence of stable configurations $c_0, c_1, ..., c_{n+1}$ such that c_0 is initial and for all $0 \leq i \leq n$, $leads(c_i, w_i, c_{i+1})$. The *leads* predicate is defined in [HKp99]. It describes the reaction of the system to a message sent from the environment to the system that causes a transition of the system from the stable configuration c_i to a new stable configuration c_{i+1}, passing through a set of unstable configurations. The trace describing this behavior is w_i.

As to Clause 2 in Def. 2, the system reaches the stable configuration c_{n+1} at the end of the reactions to η. For any object O_i and request σ, there is a reaction of the system to the directed request $O_i.\sigma$ from the stable configuration c_{n+1}. If we denote by w_{n+1} the word that captures such a reaction, w_{n+1} is in the trace set of S on $O_i.\sigma$ from c_{n+1}, from which we obtain $w \cdot w_{n+1} \in \mathcal{L}_S$.

For Clause 3, assuming that $w = x \cdot y \cdot z$, $y \in A_{in}$, there exists i with $x = w_0 \cdots w_i$ and therefore $x \in \mathcal{L}_S$.

(4) The system S satisfies the specification LS. Hence, from Clause 2 of Def. 1 we have

$$\forall m \in M, mod(m) = existential \Rightarrow \exists \eta\ \mathcal{L}_S^\eta \cap \mathcal{L}_m \neq \emptyset$$

Since $\mathcal{L}_S^\eta \subseteq \mathcal{L}_S = \cup_\eta \mathcal{L}_S^\eta$, we obtain

$$\forall m \in M, mod(m) = existential \Rightarrow \mathcal{L}_S \cap \mathcal{L}_m \neq \emptyset$$

($\Leftarrow$) Let LS be consistent. We have to show that there exists an object system S satisfying LS. To prove this we define the notion of a **global system automaton**, or a **GSA**. We will show that there exists a GSA satisfying the specification and that it can be used to construct an object system satisfying LS.

A GSA A describing a system with objects $\mathcal{O} = \{O_1, ..., O_n\}$ and message set
$\Sigma = \Sigma_{in} \cup \Sigma_{out}$ is a tuple $A = \langle Q, q_0, \delta \rangle$, where Q is a finite set of states, q_0 is the initial state, and $\delta \subseteq Q \times \mathcal{B} \times Q$ is a transition relation. Here $\mathcal{B}$ is a set of labels, each one of the form σ/τ, where $\sigma \in A_{in} = (env) \times (\mathcal{O}.\Sigma_{in})$ and $\tau \in A^*_{out} = ((\mathcal{O}) \times (\mathcal{O}.\Sigma_{out}))^*$. Let $\eta = a^0 \cdot a^1 \cdots$ where $a^i \in A_{in}$. The **trace set** of A on η is the language $\mathcal{L}^\eta_A \subseteq (A^* \cup A^\omega)$, such that a word $w = w_0 \cdot w_1 \cdot w_2 \cdots$ is in $\mathcal{L}^\eta_A$ iff $w_i = a^i \cdot x^i$, $x^i = x^{i_0} \cdots x^{i_{k_i - 1}} \in A^*_{out}$ and there exists a sequence of states $q^{0_1}, q^{1_1}, ..., q^{1_{k_1}}, q^{2_1}, ..., q^{2_{k_2}}, ...$ with $q^{0_1} = q_0$, and such that for all i, j $(q^{i_j}, /x^{i-1_j}, q^{i_{j+1}}) \in \delta$ and $(q^{i_{k_i}}, a^i/x^{i_0}, q^{i+1_1}) \in \delta$.

The satisfaction relation between a GSA and an LSC specification is defined as for object systems: the GSA A satisfies $LS = \langle M, amsg, mod \rangle$, written $A \models LS$, if $\forall m \in M, mod(m) = universal \Rightarrow \forall \eta \; \mathcal{L}^\eta_A \subseteq \mathcal{L}_m$, and $\forall m \in M$,
$mod(m) = existential \Rightarrow \exists \eta \; \mathcal{L}^\eta_A \cap \mathcal{L}_m \neq \emptyset$.

Since LS is consistent, there exists a language $\mathcal{L}_1$ as in Def. 2. Since $\mathcal{L}_1$ is regular, there exists a DFA $\mathcal{A} = (A, S, s_0, \rho, F)$ accepting it. We may assume that $\mathcal{A}$ is minimal, so all states in S are reachable and each state leads to some accepting state.

From Clause 2 of Def. 2, for every accepting state s of $\mathcal{A}$ and for every $a \in A_{in}$ there exists an outgoing transition with label a leading to a state that is connected to an accepting state by a path labeled $r \in A^*_{out}$. Formally,

$$\forall s \in F \; \forall a \in A_{in} \;\; \rho(s, a) = s' \;\; \Rightarrow \;\; \exists r \in A^*_{out} \text{ s.t. } \rho(s', r) \in F$$

From Clause 3 of Def. 2, no nonaccepting states of $\mathcal{A}$ have any outgoing transitions with label $a \in A_{in}$. This is true since if there were such a state $s \notin F$ reachable from the initial state by x, we would have $\rho(s_0, x) = s$ and $\rho(s, a) = s'$, and from s' we can reach an accepting state $\rho(s', z) \in F$. Then $w = x \cdot a \cdot z$ would violate Clause 3.

We have shown that $\mathcal{A}$ has transitions labeled by A_{in} only for accepting states, and for an accepting state there is such a transition for every letter from A_{in}. We now convert $\mathcal{A}$ into an NFA $\mathcal{A}'$ with the same properties, but, in addition, accepting states do not have outgoing transitions labeled A_{out}. This can be done by adding, for each state $s \in F$, an additional state $s' \notin F$. All incoming transitions into s are duplicated so that they also enter s' and all outgoing transitions from s labeled A_{out} are transferred to s'. $\mathcal{A}'$ accepts the same language as $\mathcal{A}$ since it can use nondeterminism to decide if to take a transition to s or s'.

We now transform the automaton $\mathcal{A}'$ into a GSA $\mathcal{B}$ by changing all transitions with a label from A_{out} into null transitions with that letter as an action. All transitions with a label from A_{in} are left unchanged.

We have to show that $\mathcal{B}$ satisfies the specification LS. From the construction of $\mathcal{B}$, we have

$$\mathcal{L}_B = \cup_\eta \mathcal{L}^\eta_B = \mathcal{L}_1$$

From Clause 1 of Def. 2, we have

$$\mathcal{L}_1 \subseteq \bigcap_{m_j \in M, mod(m_j)=universal} \mathcal{L}_{m_j}$$

Hence,

$$\forall m \in M, mod(m) = universal \Rightarrow \mathcal{L}_1 \subseteq \mathcal{L}_m,$$

yielding

$$\forall m \in M, mod(m) = universal \Rightarrow \forall \eta\ \mathcal{L}_B^\eta \subseteq \mathcal{L}_1 \subseteq \mathcal{L}_m$$

This proves Clause 1 of Def. 1.
Now, from Clause 4 of Def. 2, we have

$$\forall m \in M, mod(m) = existential \Rightarrow \mathcal{L}_m \cap \mathcal{L}_1 \neq \emptyset$$

But since $\mathcal{L}_1 = \cup_\eta \mathcal{L}_B^\eta$, this becomes

$$\forall m \in M, mod(m) = existential \Rightarrow \exists \eta\ \mathcal{L}_B^\eta \cap \mathcal{L}_m \neq \emptyset,$$

thus proving Clause 2 of Def. 1.