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► **To cite this version:**

Hai Nguyen Van, Frédéric Boulanger, Burkhart Wolff. TESL: a Model with Metric Time for Modeling and Simulation. 27th International Symposium on Temporal Representation and Reasoning, Sep 2020, Bozen-Bolzano, Italy. 10.4230/LIPICs.TIME.2020.15 . hal-02931401

HAL Id: hal-02931401

<https://hal.science/hal-02931401>

Submitted on 7 Sep 2020

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TESL: a Model with Metric Time for Modeling and Simulation

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Abstract

Real-time and distributed systems are increasingly finding their way into critical embedded systems. On one side, computations need to be achieved within specific time constraints. On the other side, computations may be spread among various units which are not necessarily sharing a global clock. Our study is focused on a specification language – named TESL – used for coordinating concurrent models with timed constraints. We explore various questions related to time when modeling systems, and aim at showing that TESL can be introduced as a reasonable balance of expressiveness and decidability to tackle issues in complex systems. This paper introduces (1) an overview of the TESL language and its main properties (polychrony, stutter-invariance, coinduction for simulation), (2) extensions to the language and their applications.

2012 ACM Subject Classification Theory of computation → Timed and hybrid models

Keywords and phrases Timed Systems, Semantics, Models, Simulation

Supplementary Material Artifacts and source code available at github.com/heron-solver/heron.

1 Introduction

Designing and modeling systems nowadays still raise open problems. A very expressive language or framework can be useful to model a complex system where events are not trivially interleaved. On the opposite, an excessively expressive language is the reason for prohibitive slow-downs or even undecidability. As such, a reasonable balance between expressiveness and decidability needs to be found. In the current industrial trend for critical embedded systems, grows an increasing need for two kinds of systems:

- *Real-Time Systems* where an external input is followed by an output delivered within a specified time, named *deadline*. The correct behavior of such systems must be ensured at both logical and temporal levels.
- *Distributed Systems* where autonomous nodes communicate and cooperate to perform a common computation.

A distributed real-time system (DRTS) [34, 14] belongs to both categories and consists in autonomous computing nodes where specific timing constraints must be met. DRTS are essential as they describe more closely common real-time applications by providing fault tolerance and load sharing [35, 34, 14]. An example of a DTRS is a modern car using CAN buses [14]. In such a setting, a middle gateway connects two CAN buses. One of them is high-speed and connects the engine, the suspension and the gearbox control. The other one is low-speed and connects the lights, seat and door control units. The aviation industry also

44 exhibits an increasing need for DTRS as shown by recent developments in interoperable
45 gateways ED-247 [21].

46 On the side of formal modeling, various environments have emerged to tackle the issue of
47 modeling and verifying complex systems. Some are industrial products, such as Matlab/Sim-
48 ulink [15], Wolfram SystemModeler [33], SCADE [7]. Some others are academic experiments,
49 such as Ptolemy II [13], TimeSquare [12], ModHel’X [20]. Our study is centered around
50 the inner formalisms that drive these environments, and in particular the TESL language.
51 The main question this paper addresses is: *Can we provide a uniform framework to model*
52 *distributed and real-time systems?* The paper is organized as follows: Section 2 introduces the
53 TESL language which we believe can answer the main problem. Section 3 introduces its main
54 properties, in terms of polychronous clocks, stutter-invariance and coinductive unfolding.
55 Finally, in Section 4 we present some extensions and aim at showing their relevance in the
56 scope we address.

57 2 The TESL language

58 The Tagged Events Specification Language (TESL) [8] originates from the idea of coordinating
59 the execution of heterogeneous inner-parts of a model as components of the ModHel’X
60 modeling and simulation environment. The language is inspired by CCSL [16, 26], the
61 Tagged Signal Model [25] and from the constructive semantics of Esterel [6, 5] for the original
62 simulation solver. In this setting, an event is modeled by a *clock*, with an associated time scale.
63 Considering a continuous system, its behavior is discretized into a sequence of observation
64 instants. At each instant, a clock admits a *timestamp* (also called *tag*), that stands for the
65 metric time measured on this clock. Besides, a clock also admits a *tick* which indicates an
66 occurrence of the event at this instant. The domain for timestamps can possibly be any
67 totally ordered set. We emphasize the fact that the language handles chronometric time
68 constraints, which are different from logical time constraints. Chronometric time constraints
69 are given on durations measured between timestamps. Two forms of constraints may be
70 specified in TESL:

- 71 ■ *Event-triggered causality.* Events may occur due to the occurrence of other events. For
72 instance “I have a coffee because my office mate prepares some coffee”.
- 73 ■ *Time-triggered causality.* Events may occur because a time threshold has been reached.
74 For instance “I have a coffee because it is 9am”.

75 2.1 Illustrating the Language

76 Let us model in TESL the simple behavior of a radiotherapy machine used in cancer treatment.
77 The patient has a prescription of 2 Gy of radiation in low-dose-rate of 1.5 Gy.h⁻¹.

■ Listing 1 Radiotherapy machine

```

78
79 1  rational-clock hr           // Time unit in hours
80 2  rational-clock gy         // Radiation unit in Gray
81 3  unit-clock    start sporadic () // Start emitting rays
82 4  unit-clock    stop           // Stop emitting rays
83 5  unit-clock    emstop         // Emergency stop
84 6  time relation gy = 1.5 * hr
85 7  start time delayed by 2.0 on gy implies stop
86 8  emstop implies stop
87

```



■ **Figure 1** Two partially satisfying runs

88 Lines 1 to 5 declare clocks `hr` and `gy` with rational timestamps, and clocks `start`, `stop`
 89 and `emstop` with the unit timestamp (so there is no chronometric scale associated to them).
 90 The constraint `sporadic` enforces the occurrence of a tick on `start`. Line 6 specifies that
 91 time on `hr` flows 1.5 times as fast as on `gy`. Line 7 specifies that each time clock `start` ticks,
 92 clock `stop` will tick after a delay of 2.0 measured on the time scale of clock `gy`. Line 8
 93 requires that each time the `emstop` clock ticks, the `stop` clock instantaneously ticks as well.
 94 The syntax of such expressions is detailed in Subsection 2.3.

95 Two behaviors are illustrated in Figure 1. They show possible execution traces or *runs*
 96 satisfying the TESL specification. A run consists in a sequence of synchronization *instants*
 97 (vertical dashed line with blue numbers). Each of them contains *ticks* (in red) along with
 98 *timestamps* (in green) on the time-scales of the clocks `hr`, `gy`, `start`, `stop` and `emstop`.

99 2.2 Clocks, runs and timestamps

100 ► **Definition 1.** Let \mathbb{K} be the set of clocks, \mathbb{B} the set of booleans and \mathbb{T} the ordered domain
 101 of timestamps. The set of runs is denoted Σ^\times and defined by

$$102 \quad \Sigma^\times = \mathbb{N} \rightarrow \mathbb{K} \rightarrow (\mathbb{B} \times \mathbb{T})$$

103 Additionally, we define two projections that extract the components of an event occurrence:

104 $\text{ticks}(\rho \ n \ K)$ ticking predicate of clock K in run ρ at instant n (first projection)

105 $\text{time}(\rho \ n \ K)$ time value on clock K in run ρ at instant n (second projection)

106 ► **Example 2.** Let $\rho_{\text{Fig.1a}}$ be the run shown in Figure 1a, we have $\text{ticks}(\rho_{\text{Fig.1a}} \ 0 \ \text{start}) = \text{true}$
 107 and $\text{time}(\rho_{\text{Fig.1a}} \ 1 \ \text{gy}) = 2.0$.

108 2.3 Quick overview of the syntax

109 We briefly introduce some expressions of the language which serve the purpose of this paper.
 110 The reader may refer to the official website of TESL¹ for an exhaustive description of all the
 111 features of the language. A TESL specification Φ is described by the following grammar:

¹ <https://wdi.centralesupelec.fr/software/TESL/>

```

112   $\Phi$  ::=  $\langle atom \rangle \wedge \dots \wedge \langle atom \rangle$ 
113   $\langle atom \rangle$  ::=  $\langle clock \rangle$  sporadic  $\langle timestamp \rangle$  on  $\langle clock \rangle$ 
114             |  $\langle clock \rangle$  implies  $\langle clock \rangle$ 
115             | time relation ( $\langle clock \rangle$ ,  $\langle clock \rangle$ )  $\in$   $\langle relation \rangle$ 
116             |  $\langle clock \rangle$  time delayed by  $\langle duration \rangle$  on  $\langle clock \rangle$  implies  $\langle clock \rangle$ 

```

118 where $\langle clock \rangle \in \mathbb{K}$, $\langle timestamp \rangle \in \mathbb{T}$, $\langle duration \rangle \in \mathbb{T}$ and $\langle relation \rangle \subseteq \mathbb{T} \times \mathbb{T}$.

119 To provide a quick understanding, we briefly and informally explain the semantics:

- 120 ■ K **sporadic** τ **on** K_{meas} requires a tick on clock K at an instant where the timestamp on K_{meas} is τ ;
- 122 ■ K_{master} **implies** K_{slave} models instantaneous causality by specifying that at each instant where K_{master} ticks, K_{slave} ticks as well ;
- 124 ■ **time relation** (K_1, K_2) $\in R$ relates the time frames of clocks K_1 and K_2 by specifying that at each instant, the timestamps on K_1 and K_2 have to be in relation R ;
- 126 ■ K_{master} **time delayed by** $\delta\tau$ **on** K_{meas} **implies** K_{slave} stands for delayed causality by duration. At each instant k where K_{master} ticks, it requires a tick on K_{slave} at an instant where the timestamp on K_{meas} is τ' , with τ' the sum of $\delta\tau$ and the timestamp on K_{meas} at instant k . In other words, it states that each tick on K_{master} must be followed by a tick on K_{slave} after a delay $\delta\tau$ measured on the time scale of K_{meas} .

131 3 Properties of the language

132 3.1 Polychronous clocks and time islands

133 One of the most prominent properties of the TESL language lies in *polychronous clocks* [23], a *global clock* does not necessarily drive the system. In the context of distributed systems, there exists as many clocks as there are computing nodes: all run at different rates and their clocks may possibly drift along. This is why, an additional mechanism of *synchronization* is necessary to coordinate these subworkers to achieve a common desired computation.

- 138 ■ *Metric level.* There are similarities with time dilation as in *special relativity* [19] where time seems to flow more slowly for a stationary observer than for a moving observer. The drift increases with the speed of the moving observer. For instance, GPS satellites suffer from time drifting and it is necessary to take into account these effects.
- 142 ■ *Temporal level.* Modern computing also exhibits this idea where temporal cycles may speed up or slow down. Current predominant processors adjust their clock speed with respect to environmental variables (energy, heat, noise), this is called *throttling*. Today's multicore processors consist of multiple computing units which may run faster or slower for these reasons, while possibly being used to achieve a distributed computation.

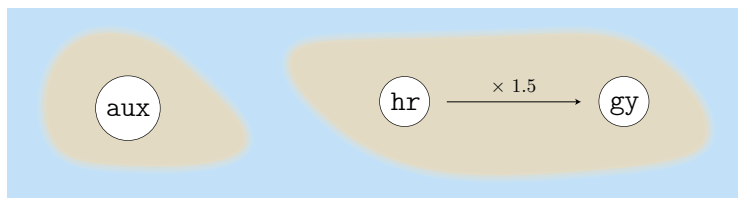
147 We illustrate this statement with the running example by adding an independent computing unit used for auxiliary computation needs. Whenever its computation is finished, it will trigger an event to indicate that it is ready. Let us simply declare a clock `aux` whenever this computing unit yields its signal. Besides, we can also create a scenario where we require this to occur at timestamp 0.5. The following line can be added to the specification in Listing 1:

```

152
153
154 rational-clock aux sporadic 0.5

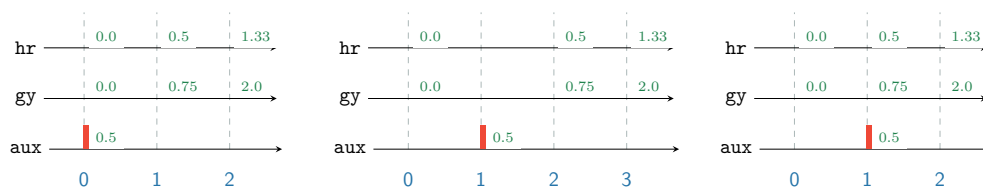
```

156 In this setting, clocks `hr` and `gy` are said to belong to the same *time island* as their
 157 timeframes are arithmetically related. On the other hand, clock `aux` belongs to another
 158 independent time island. There may also be other clocks living around as the specification is
 159 permissive and allows other clocks to exist even though they were not specified.



■ **Figure 2** Graphic representation of time islands

160 Let us consider the specification in Listing 1, with the additional `aux` clock as declared
 161 above. Figure 3 depicts three runs which satisfy this specification. For presentation purposes,
 162 only three clocks `hr`, `gy` and `aux` are displayed. On the leftmost figure, we observe that `aux`
 163 ticks at 0.5 when it is 0.0 on `hr`. On the center figure, `aux` ticks at 0.5 when it is between
 164 0.0 and 0.5 on `hr`. On the rightmost figure, `aux` ticks at 0.5 when it is 0.5 on `hr`. We see
 165 therefore that there exists an infinite number of satisfying runs as the timeframe on clock `aux`
 166 is left completely unrelated to the other time frames. However, we developed a simulation
 167 solver for TESL that supports symbolic runs, and hence captures this infinity of runs in a
 168 finite number of symbolic runs using symbolic timestamps.



■ **Figure 3** Examples of satisfying runs with additional clock `aux` in an independent time island

169 3.2 Stutter Invariance

170 A fundamental concept of concurrent and distributed systems is *stutter invariance*. In
 171 finite-state model checking, it is an essential requirement for partial-order reduction tech-
 172 niques. When composing automata, the addition of stutter, or silent instants, allows the
 173 accommodation for their different alphabets. From a point of view in language theory, the
 174 membership of any word in a language shall be preserved even if a letter is duplicated. In
 175 our setting to model and compose submodels, we need stutter invariance in order to provide
 176 *compositionality*. For instance, when composing two specifications, we may have to add
 177 observation instants to a run that satisfies a specification in order to observe events on
 178 clocks that belong to the other specification. In other words, stuttering is necessary to refine
 179 specifications [22]. Stutter invariance also allows one to observe a model more often than
 180 necessary without changing its behavior.

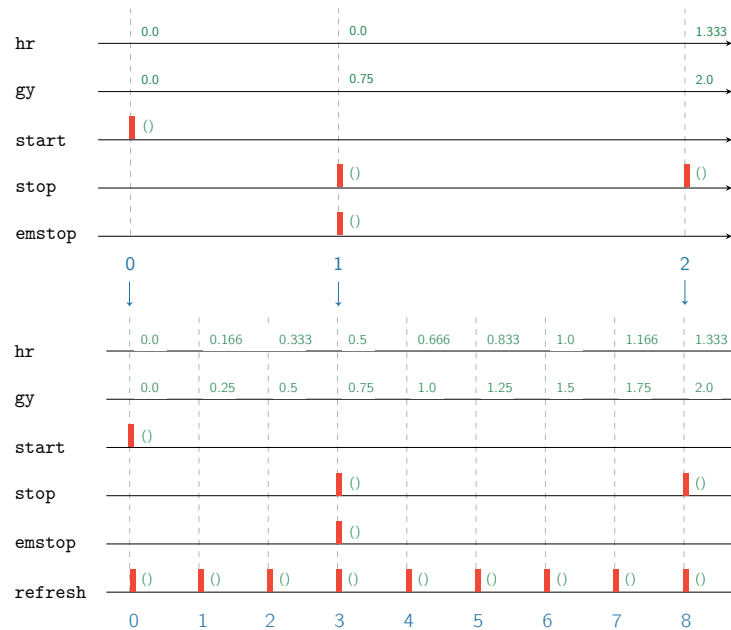
181 In TESL, composing specifications is simply performed by the conjunction of TESL-
 182 formulae. To illustrate the idea of stutter-invariance with the running example, let us assume
 183 that we require the system to trigger some refresh mechanism every 10 minutes. We would
 184 add the following lines to the specification:

185
186
187
188
189

```
refresh sporadic 0.0 on hr
refresh time delayed by <10/60> on hr implies refresh
```

190 If we consider the run from Figure 1b and wish to compose it with this refreshing
 191 mechanism, a satisfying run is shown in Figure 4. The top of the figure shows the original
 192 run as in Figure 1b, whereas the bottom depicts a run where new instants have been added.
 193 A one-to-one correspondence is observed between run instants in the top and the bottom
 194 figure. Both runs exhibit the same first instant where `start` is triggered, with `refresh`
 195 additionally ticking in the second run. However, the second instant of the second run exists
 196 due to the refreshing requirement at 0.166 on clock `hr`, which is not present on top.

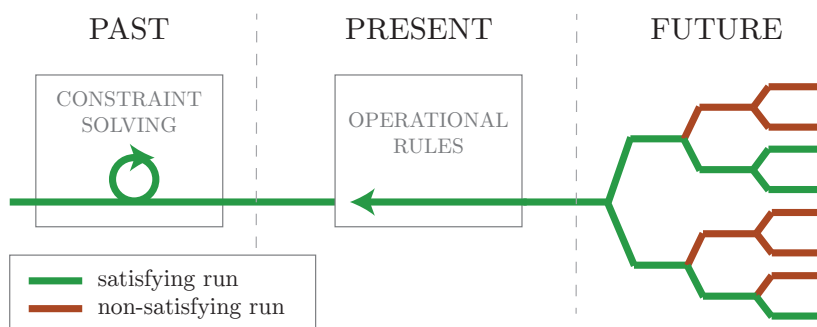
197 Stutter-invariance is illustrated by the fact that a run may be dilated and new instants
 198 added while still satisfying the specification.



■ **Figure 4** The example of radiotherapy run diluted

199 3.3 Unfolding Specifications

200 The language allows the specification of runs that can be constructed and described by
 201 operational rules. In [29], we introduced an operational semantics of the language whose
 202 main ideas are summarized in Figure 5. The general concept of the operational semantics
 203 revolves around a 3-component pattern *past-present-future*. The past component contains
 204 the run we are constructing (which we also call the *run context*), the present component
 205 contains TESL-formulae to consume for the construction of the current instant, while the
 206 future component contains TESL-formulae to consume for future instants. The system
 207 considers each TESL formula as a consumable resource, and its consumption produces a
 208 “smaller” resource, which allows to constructively build the past component. Finally, the past
 209 component is a symbolic run and contains logical primitives which are sent to a SMT-solver
 210 in order to decide the satisfiability of the constructed run. Put differently, we reduced the
 211 problem of solving a TESL specification to a simpler constraint solving problem.



■ **Figure 5** Usage of the operational semantics

4 Extensions

212

213 In this section, we propose two extensions of the language. From the original implementation
 214 of TESL, we have experimentally broadened its scope by adding two features on formulae and
 215 clocks. The addition of such has increased the language expressiveness without compromising
 216 constraint solving. To provide an insight, we illustrate them with an application example.
 217 We designed and experimented their semantics by implementing them into an experimental
 218 solver, named Heron² [29]. This implementation is a path-exhaustive multicore simulation
 219 solver built with MLton/MPL [36, 37]. It directly implements the operational semantics and
 220 the presented extensions. It can also be used for system testing and monitoring.

4.1 Precedence formula (and timed automata)

221

222 The first extension we propose is built around the precedence operator as found in CCSL.
 223 A appreciable motivation lies in modeling Synchronous Dataflows [24, 26]. In this model,
 224 each component provides an interface with inputs and outputs, and respectively a number of
 225 input tokens (to be read) and another of output tokens (to be written). When wiring two
 226 components, it is necessary that the n -th output writing event will precede the n -th input
 227 reading event. Precedence allows to specify this kind of indexed requirement over the order
 228 of event occurrence.

229

We extend the syntax of TESL as shown in Subsection 2.3 with

230

$$\begin{array}{lcl}
 \langle atom \rangle & ::= & \dots \\
 & | & \langle clock \rangle \text{ weakly precedes } \langle clock \rangle \\
 & | & \langle clock \rangle \text{ strictly precedes } \langle clock \rangle
 \end{array}$$

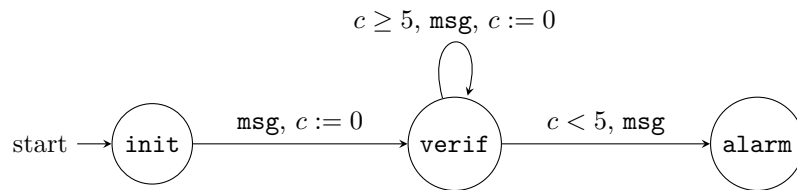
232

234 Informally, K_1 **weakly precedes** K_2 means that each tick on clock K_2 may be uniquely
 235 mapped to a tick on K_1 in the past or current instants (as a one-to-one correspondence).
 236 K_1 **strictly precedes** K_2 is analogous but maps to instants that are strictly in the past.

237 ► **Remark 3.** Mallet *et al.* showed that the decidability of this type of formula could be
 238 handled with counter automata [27]. In our framework, we modeled this formula in a similar
 239 way by embedding run contexts with arithmetic constraints containing counter expressions.
 240 Again, we reduced this problem to a constraint solving problem.

² <https://github.com/heron-solver/heron>

241 To illustrate our interest in this operator, we consider timed automata [2, 1] as introduced
 242 by Alur and Dill. An additional and distinct mechanism made of clocks (also referred as
 243 *chronometers*) is used to store and specify metric timing constraints. On the implementation
 244 side, they extend classical finite-state automata with timing constraints. This formalism
 245 allows time to progress inside states while transitions are instantaneous, meaning that
 246 transitioning from one state to another is fast enough to be abstracted. In this subsection, we
 247 describe how this model of computation can be encoded with TESL extended with precedence.
 248 Let us give in Figure 6 a simple timed automaton (extracted from [4]) which models a system
 249 in which an alarm is triggered whenever the delay between receiving two messages is less
 250 than 5 seconds.



■ **Figure 6** An example of timed automata from [4]

251 To model the timed automaton in Figure 6, we declare TESL-clocks that will simulate
 252 the events occurring at a lower level (suffixed by `_enter` and `_leave`). Other clocks are also
 253 declared for transitions.

```

254
255 // Set of states: {init, verif, alarm}
256 unit-clock state_init_enter
257 unit-clock state_init_leave
258 unit-clock state_verif_enter
259 unit-clock state_verif_leave
260 unit-clock state_alarm_enter
261 unit-clock state_alarm_leave
262
263

```

264 We also need to declare TESL-clocks related to the behavior of TA-clocks, in particular
 265 when resetting them.

```

266 // Set of clocks: {c}
267 unit-clock c_reset
268 rational-clock c sporadic 0.0
269
270

```

271 Likewise, we need a TESL-clock to model the reading of a symbol (so-called *action*).

```

272 // Set of actions: {msg}
273 unit-clock read_msg
274
275

```

276 We proceed by encoding in TESL each transition of the timed automaton. We model the
 277 first transition from `init` to `verif`, which must read symbol `msg` and reset clock `c`, as:

```

278 // Transition t1 = init -> verif: msg, c := 0
279 state_init_leave when read_msg implies trigger_t1
280 trigger_t1 implies state_verif_enter
281 trigger_t1 implies c_reset
282
283

```

284 The second transition from `verif` to itself can be triggered when reading `msg` if time on
 285 clock `c` is greater than or equal to 5, which will eventually lead to resetting `c`. This means

286 that the transition can be triggered if more than 5.0 units of time have elapsed on c since
 287 the last time c has been reset. When using this transition, one will remain in state `verif`
 288 while resetting c to 0 each time a message has been read.

```
289 // Transition t2 = verific -> verific: c >= 5, msg, c := 0
290 c_reset time delayed by 5.0 on c with reset on trigger_t3
291     implies trigger_t2_min
292 trigger_t2_min weakly precedes trigger_t2
293 state_verif_leave ^ read_msg implies trigger_t2 ∨ trigger_t3
294 trigger_t2 implies state_verif_enter
295 trigger_t2 implies c_reset
296
297
```

298 The third transition from `verif` to `alarm` is triggered when a new message has been
 299 received before 5.0 units of time have elapsed. We model this as:

```
300 // Transition t3 = verific -> alarm: c < 5, msg
301 c_reset time delayed by 5.0 on c with reset on trigger_t2
302     implies trigger_t3_max
303 trigger_t3 strictly precedes trigger_t3_max
304 state_verif_leave ^ read_msg implies trigger_t2 ∨ trigger_t3
305 trigger_t3 implies state_alarm_enter
306
307
```

308 Figure 7 shows a run prefix exhibiting the behavior of our encoding of the timed automaton.
 309 At instant 0, time on clock c is 0.0 and we enter in state `init`. At instant 1, 5.0 units of time
 310 have elapsed. At instant 2, 5.0 additional units of time have elapsed and `read_msg` has been
 311 triggered, thus the transition is triggered (`trigger_t1`). The TA-clock c is reset and leaves
 312 state `init` to enter `verif`. Also, a minimum limit has been set on triggering transition t_2 as
 313 it can only be fired after elapsing at least 5.0 units of time (as depicted by `trigger_t2_min`
 314 at instant 4). At instant 4, symbol `msg` is read and transition t_2 is triggered to re-enter in
 315 the same state `verif`. Finally, at instant 5, the symbol `msg` is read again and transition t_3 is
 316 triggered to enter `alarm`. A tick on `trigger_t3` is possible as it precedes `trigger_t3_max`.
 317 Likewise, `trigger_t3_max` defines a maximum limit to ensure any t_3 -transition triggering
 318 only before.

319 4.2 Previous operator (and PID controllers)

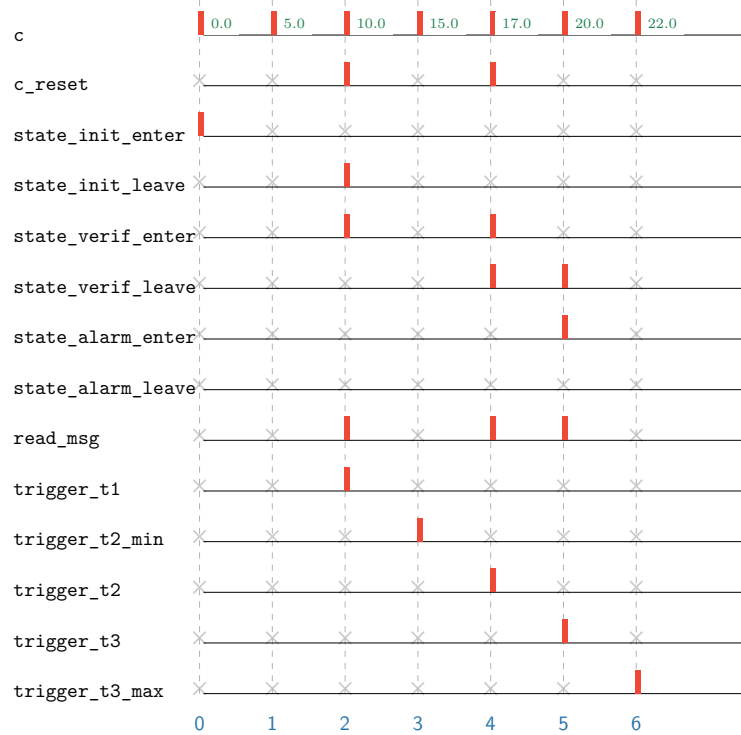
320 Another useful operator is `pre` with similar syntax and semantics as in Lustre [18]. This
 321 operator simply allows to refer to the previous timestamp on a clock. Hence, a substantial
 322 part of feedback systems can be modeled accurately as they require registers to store previous
 323 values. The power of computation is significantly augmented and allows us to model more
 324 complex systems, such as mathematical sequences and series (*e.g.*, Fibonacci), differential
 325 calculus (derivatives, Euler’s integrator), or digital filters.

326 Since this operator refers to the value of a signal at a previous instant, we generalized
 327 TESL clocks as *flows*. A flow is a clock where timestamps are no longer required to be
 328 monotonic. As a matter of fact, these “timestamps” are simply called *values*.

329 We extend the syntax of TESL as shown in Subsection 2.3, with:

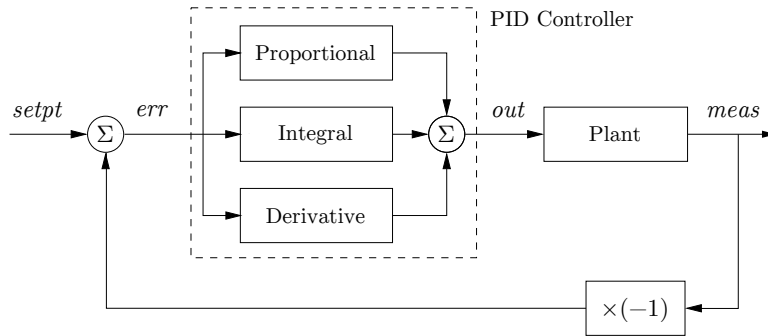
$$330 \begin{array}{l} \langle clock \rangle \quad ::= \quad K \in \mathbb{K} \\ \quad \quad \quad | \quad \text{pre } \langle clock \rangle \end{array}$$

333 This extension is useful at modeling feedback systems. Let us illustrate this with the
 334 ubiquitous algorithm of automatic control theory: the Proportional-integral-derivative (PID)



■ **Figure 7** A satisfying run prefix to encode a timed automaton

335 controller [39]. In this theory, a PID controller delivers a control signal to a process in order
 336 to bring a process output closer to a reference setpoint (*e.g.*, cruise control in cars, autopilots
 337 in airplanes).



■ **Figure 8** General diagram of a process using a PID controller

338 The block diagram in Figure 8 shows the structure of the controller. Basically, the system
 339 receives as input the error signal **err**, *i.e.* the difference between the reference setpoint
 340 **setpt** and the process output **out**, and computes a control signal based on the sum of a term
 341 proportional to the error, an integral term and a derivative term. Each of the three terms
 342 is parameterized by a multiplying factor, respectively K_p , K_i and K_d , which are commonly
 343 called *gains*. Thereafter, the controller output enters a *transfer function* which translates
 344 the control signal **out** into the process output **meas**. For instance in automotive control
 345 theory, this occurs when converting the position of the gas pedal into the generated car

346 velocity. This new output will be used to feed the error back at the next computing cycle. It
 347 is possible to describe this system straightforwardly in TESL as in Listing 2.

348

■ **Listing 2** The PID controller

349

```

350 // Time
351 time relation dt = 1.0
352 time relation t = [0.0] -> (pre t) + dt
353 // Gain
354 time relation Kp = 0.1
355 time relation Ki = 0.2
356 time relation Kd = 0.2
357 // Setpoint
358 time relation setpt = 40.0
359 // Control signal
360 time relation err = setpt - meas
361 time relation integr = [0.0] -> (pre integr) + (err * dt)
362 time relation derivat = [0.0] -> (err - (pre err)) / dt
363 time relation out = (Kp * err) + (Ki * integr) + (Kd * derivat)
364 // Simple actuation
365 time relation meas = [0.0] -> (pre meas) + (pre out)
366
```

367 When running this example, the solver yields the output shown by the extract in Listing 3.

368

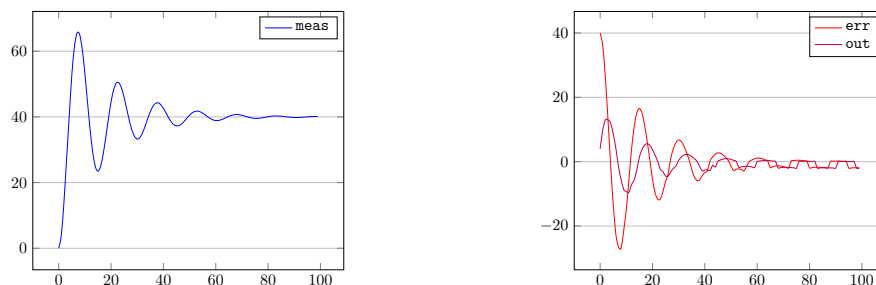
■ **Listing 3** An extract of the satisfying run found by Heron of the PID controller

369

```

370 ### Solver has successfully returned 1 model
371 ## Simulation result [0x1ADAB]:
372      meas      err      integr      derivat      out
373 [1]      0.0      40.0         0.0         0.0         4.0
374 [2]      4.0      36.0        36.0        -4.0        10.0
375 [3]     14.0      26.0        62.0       -10.0        13.0
376 [4]     27.0      13.0        75.0       -13.0        13.0
377 [5]     40.0      -1.0        74.0       -14.0        12.0
378 ...
```

380 Additionally, the values of the flows `meas`, `err` and `out` are plotted in Figure 9. As
 381 expected, we observe that the process output `meas` is brought closer to the reference setpoint
 382 `setpt = 40.0`. Besides, the error signal and the control signal `out` gradually decrease to 0.0
 383 as the need to damp out oscillations progressively decreases.



■ **Figure 9** Plotting values for `meas`, `err` and `out`

384 **5** Related Work

385 In the family of synchronous programming languages [3], Lustre [18], Esterel [6, 5] and
 386 Signal [17] are known to provide polymorphic time (time domains of various type). However,
 387 their time model is purely logical, which is not suited when dealing with modeling non-
 388 discretizable systems. Prelude [32] and Zélus [9] overcome this with continuous dynamics.

389 All these previous models derive clocks from a global root clock, which constrains models
 390 to flow from a single reaction clock. Polychrony (clocks possibly living in various independent
 391 timeframes) overcomes this restriction by allowing specifications with more relaxed and
 392 concurrent execution of systems. This feature can be observed in the Signal language or
 393 polychronous automata [23]. Compared to TESL, they do not allow metric time constraints.

394 TESL is also inspired by CCSL which supports asynchronous constraints on events. It
 395 admits an executable [38] and denotational semantics [11, 28]. However, time in CCSL is
 396 purely logical and durations are counted as a number of ticks on a clock.

397 On a more theoretical-side, timed automata [2, 1] support both discrete events and metric
 398 time. However, clocks are global and uniform, they necessarily progress at the same rate.

399 All in all, TESL attempts to overcome these limitations and provides a general-purpose
 400 specification language of synchronous and asynchronous constraints with clocks over poly-
 401 morphic time while supporting polychrony, and mixing logical and metric time.

402 **6** Future work

403 The outcome of our study leads us to various future opportunities:

- 404 ■ An effort is currently running towards a machine-checkable formalization of the operational
 405 and denotational semantics into the Isabelle/HOL proof assistant [31, 30]. We successfully
 406 proved that the operational semantics was correct and complete with respect to the
 407 denotational semantics. Proving both extensions of the paper is a future direction.
- 408 ■ Numerous questions about model-checking remain unanswered. In our experiments, we
 409 have observed that unfolded specifications could be refolded with abstract interpretation
 410 techniques. This would offer a finite-representation of these infinite-state systems, thereby
 411 providing means to decide safety and liveness properties of such systems.
- 412 ■ In addition, the TESL language seems to be suited for modeling and simulation of systems
 413 with time of various kind. With the new extensions we propose and their implementation
 414 in an existing efficient solver, we believe TESL can become a relevant asset as a simulation
 415 engine for simulation platforms, such as the GEMOC Studio [10].

416 **7** Conclusion

417 This study introduces a language – named TESL – suited for the modeling and simulation
 418 of complex systems with multi-level time considerations. For this purpose, we illustrated
 419 how the language is suited for various applications of time in models. We first illustrated the
 420 main properties of the language (absence of a global root clock, stutter invariance). Then,
 421 we introduced two extensions of the language along with two applications depicted by (1) an
 422 encoding of timed automata, and (2) an implementation of a PID controller.

423 Most of the widely used formalisms suffer from restrictions in their model of time, which
 424 we attempt to address. Some consider time as purely logical and may not be suited for
 425 real-time systems as computing cycles may not necessarily flow at a fixed rate. Some other
 426 consider time as global which is restrictive towards distributed systems where time does not
 427 flow at the same rate in the different components, and may not be synchronized. We believe

our approach is complementary to state-of-the-art environments and may help to circumvent their drawbacks by considering time in its whole nature.

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