A Verification of a Process Supervisor*

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Abstract

In this paper we present a work in progress on the formal verification of a process supervisor using the McErlang model checker. The process supervisor is an alternative implementation of the standard supervisor behaviour of Erlang/OTP. This implementation, in use at the company LambdaStream, was checked against several safety and liveness properties.

1 Introduction

Writing correct concurrent software is a hard task given the inherit non-deterministic behaviour of such systems. Concurrent declarative languages seem to be an interesting and practical choice to implement concurrent software due to the absence of side-effects (or at least a much smaller number of them). For example, the concurrent functional language Erlang [5] is being used by several companies worldwide to implement complex concurrent control systems.

A technique which is often used to check that a concurrent program fulfills a set of desirable properties is *model checking* [9]. In model checking, in theory, all the states of (a model of) a concurrent system are systematically explored to check for safety requirements such as absence of deadlocks and similar critical situations that can cause the system to misbehave. For instance, McErlang [7], a model checker for programs written in Erlang, uses directly the actual Erlang source code as the model to be analyzed. McErlang has been successfully applied in a number of case studies, such as a Video–on–demand server [6], leader election protocols [7], the control software for elevators, and multi-agent systems playing for robotic soccer [4].

An example of a company using Erlang is LambdaStream S.L., which is interested in improving their software quality as shown by their participation in a European research project on property-based testing (ProTest[1]). Thanks to this project, a fruitful collaboration has been established between developers at LambdaStream and researchers at the University of A Coruña and the Universidad Politécnica de Madrid. One example of this collaboration is the experience on the verification using McErlang of properties of some LambdaStream components, as McErlang model checker is well suited to verify this

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[1] http://www.protest-project.eu/

class of concurrent software components.

In this paper we describe the experience on checking several properties on LambdaStream's supervisor component using McErlang. A process supervisor is responsible for starting, stopping, and monitoring its child processes. Testing and reproducing errors in such code is intrinsically difficult due to its non-deterministic behaviour, asynchronous communication, timing, etc. At the same time, it is crucial to establish the reliability of that critical software component because it is integrated into several software systems at LambdaStream. Although the supervisor has been in use in several products for some time and it was well tested by both the developers and a specific testing team, a discrepancy between the component specification and the actual implementation of the component was identified.

The rest of this paper is organized as follows. A brief introduction to Erlang and McErlang is found in Section 2. The description of the process supervisor component is given in Section 3 together with a brief description of the properties we have considered. The implementation of such properties and the experimental results of checking them with McErlang is explained in Section 4. Finally, some conclusions and future work are discussed in Section 5.

2 Background

2.1 The Erlang Programming Language

Erlang [1,5] is a concurrent programming language and run-time system. The sequential subset of the language is a dynamically typed functional programming language with strict evaluation. Concurrency is achieved by lightweight processes communicating through asynchronous message passing. Erlang has no construct inducing side-effects with the exception of communications among processes[2]. Expressions are evaluated eagerly similarly to, for instance, Standard ML.

What makes Erlang different from other functional languages is its support for concurrency and distribution. With Erlang's primitives for concurrency, it resembles formal calculi such as Milner's CCS [10] or Hoare's CSP [8]. Because of the absence of side-effects, limited to explicit inter-process communications, concurrent programming is far simpler compared to standard imperative languages. An Erlang virtual machine (node, in Erlang terminology) hosts several Erlang processes running concurrently. Usually, an Erlang node is mapped to an operating system process; an Erlang process is, in fact, a lightweight user-level thread with very little creation and context-switching overheads.

A distributed Erlang application consists of processes running in several nodes, possibly at different (physical or virtual) computers. Even though the initialization and management of each node is platform dependent, the nice feature is that communication among remote processes is equivalent in a distributed framework, though remote communications are less efficient, of course.

Fault-tolerance in Erlang is achieved by linking processes together in order to detect and possibly recover from abnormal process termination. Abnormal termination occurs if, for example, a function tries to access the tail of an empty list. Processes linked to the process that terminated abnormally are notified of the termination, and can thus take corrective action, i.e., possibly restarting the failed process. Process links are always bidirectional but the treatment of process termination notifications may differ between the two parties.

Handling a large number of processes easily turns into an unmanageable task, and therefore Erlang programmers mostly work with higher-level language components provided by libraries. The OTP (Open Telecom Platform) component library [12] is by far the most widely used library, offering several behaviours (design patterns in Erlang) that can be instantiated with concrete callback functions. For example, OTP behaviours include, among oth-

[2] Strictly speaking this is not true as Erlang has a process registry with side effects, and various libraries offering mutable data structures. The use of such features in Erlang, however, tends to be greatly reduced compared to other programming languages.

ers, generic servers (for client-server communication), finite state machines, or a supervisor component for structuring fault-tolerant systems hierarchically, where a parent supervisor is responsible for supervising and managing its children (work processes).

2.2 The McErlang model checker

McErlang [7] is a tool for model checking Erlang programs. The input to McErlang is the Erlang program we want to verify together with the property of interest. The fact that the program is the model facilitates the use in real-world development.

As the model checking tool is itself implemented in Erlang we benefit from the advantages that a dynamically typed functional programming language offers: easy prototyping and experimentation with new verification algorithms, rich executable models that use complex data structures directly programmed in Erlang, the ability to deal with executable models interchangeably as programs (to be executed directly by the Erlang interpreter) and data, etc.

In order to use Erlang programs as models, McErlang undergoes a source-to-source transformation to prepare the program for running under the model checker. Then, the actual Erlang compiler translates the program to Erlang byte code. Finally the program runs under the McErlang run-time system, under the control of a verification algorithm, using the regular Erlang byte-code interpreter. The pure computation part of the code (i.e, code with no side effects) and memory management (including garbage collection), is carried out by the normal Erlang run time system. However, the side effect part is executed under the McErlang run-time system, which is a complete rewrite in Erlang of the basic process creating, scheduling, communication and fault-handling machinery of Erlang. Naturally, the new runtime system offers easy check pointing (capturing the state of all nodes and processes, of the message mailboxes of all processes, and all messages in transit between processes) of the whole program state as a feature.

The steps required to perform model checking with McErlang are the following:

1. **Create the model.** Use directly the Erlang program. McErlang provides support for virtually the full language, full data type support, support for general process communication, node semantics (inter-process communication behaves in a subtly different way from intra-process communication), fault detection and fault tolerance, and crucially can verify programs written using the high-level OTP Erlang component library used by most Erlang programs.

2. **Formulate correctness properties.** Write down the properties to verify as either a *safety monitor* or a formula in linear temporal logic (LTL).

   A safety monitor is used to verify safety properties (*something bad never happens*), by keeping an internal state to check the properties at each state the program to verify reaches. Given a program and a monitor, McErlang runs them in lockstep letting the monitor investigate each new program state generated. If the property does not hold, a counterexample (an execution trace) is generated. Monitors are capable of observing both the shape of the system (e.g., which processes are alive) and significant system events (e.g., messages sent between processes).

   Some properties cannot be expressed with safety monitors, for example, liveness properties (*something good eventually happens*). In McErlang one can express such properties in Lineal Temporal Logic (LTL), and use the LTL2Buchi tool [11] to automatically translate an LTL formula into a Büchi automaton [3].

3. **Generate scenarios.** Model checking is typically a memory intensive operation, and frequently completely verifying a large system may require more computer memory than is available. As an alternative to verifying the whole system

at once we instead specify a sizeable number of smaller system *scenarios*, specifying both system configuration and process communications, such that each scenario is small enough to admit complete verification. As an example, if the system to verify is a client/server architecture, we verify a sizeable number of client–server configurations varying the number of clients, and varying the requests that clients issue to the servers.

3 Case Study: Supervisor Process

3.1 The Notion of Supervision

A supervisor is a process in charge of starting, stopping and monitoring a set of children (processes). Basically whenever a child process terminates the supervisor should restart it, i.e., spawn a new process executing the task of the terminated child. A supervisor typically supervises not only process workers, but also other supervisors, defining a hierarchical structure as shown in the example of Fig. 1.

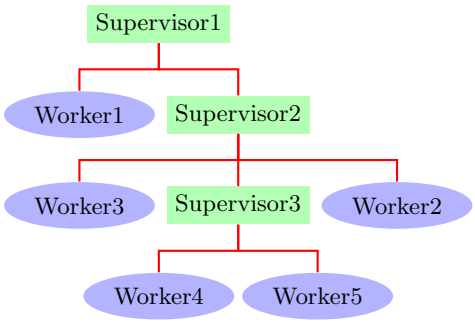


Figure 1: A supervision tree.

There are several strategies of how a supervisor process should handle the event of an abnormal termination of a child. The two main policies are:

- `one_for_one`: If a child process terminates, only that process is restarted.
- `one_for_all`: If a child process terminates, all other child processes are terminated and then all children, including the originally terminated process, are restarted.

There is usually a mechanism to prevent a situation where a process repeatedly terminates for the same reason, only to be immediately restarted again. This mechanism involves a maximum *restart intensity*. When a child reaches this restart intensity, the supervisor terminates all the child processes and then itself.

As the supervision tree is hierarchical, when a lower-level supervisor terminates, then the next higher level supervisor can take corrective action. That is, either restarting the terminated supervisor (and its subsystem of processes), or terminating itself if the error can not be handled on that level of the supervision tree.

In addition to the restart policy, the creation and termination order of children must be also specified in the supervisor.

3.2 Supervisor Implementation

There is a standard implementation of the supervisor behaviour provided by the open source distribution of Erlang/OTP. In this case study, we used an implementation of a supervisor process slightly different from the OTP implementation. This variant (from now on *nos_supervisor*) was implemented by the company LambdaStream because they wanted a more configurable supervisor to easily integrate into its products. In particular, different restarting policies are allowed for each child node in nos_supervisor.

Following the specification for a child, a child process is spawned by a supervisor process. In the nos_supervisor a child specification is a tuple:

```
{Id, StartFun, RestartFun,
RestartStrategy, RestartIntensity,
Shutdown, Options}
```

- `Id` is a name that is used to identify the child specification internally by the supervisor.

- `StartFun` defines the function call used to start the child.
- `RestartFun` defines the function call to restart the child.
- `RestartStrategy`. When a child process crashes/dies, if its restart strategy is `child`, only this child will be restarted. If its restart strategy is `all`, all the children will be stopped in reverse start order, and they will be restarted (including the offending one) in start order.
- `RestartIntensity`: either a tuple {`MaxR,MaxT,Finally`} or `infinity`:
  - {`MaxR,MaxT,Finally`}. If a child is restarted `MaxR` times in `MaxT` or less seconds, the `Finally` action is triggered:
    - `Finally==kill_sup`. The supervisor shuts down its living children in reverse start order, and then it terminates.
    - `Finally==stop_child`. The offending child is not restarted. Remaining children continue restarting normally.
  - `infinity`. If a child terminates, the supervisor will always try to restart it.
- `Shutdown`. The shutdown strategy is the same as in the OTP supervisor.
  - `brutal_kill`. Supervisor kills processes, i.e., a child process `P` will be unconditionally terminated by the supervisor sending an `exit(P,kill)` message.
  - `infinity`. The supervisor will inform the child process that it should terminate and then wait to receive an exit signal from the child signaling that it indeed has terminated.
  - `Timeout` (integer). As in `infinity` but if no exit signal is received from the child within the specified time, the child process is unconditionally terminated.
- `Options` is a list of options where an option can be either `insistent_restart` meaning that restart function failures are treated as process crashes instead of restart errors, or {`notify,pid()`} which makes the supervisor send notification messages to the specified process identifier.

3.3 Properties of the nos_supervisor

By reading the nos_supervisor documentation we came up with many interesting properties to verify for the nos_supervisor implementation. As a trivial example, we wanted to check that a child that has terminated is actually restarted by its supervisor. We also focused on properties regarding the different restart intensities and the shutdown strategies, checking all combinations of those options. For example, we formulated and checked a property that states that if there is any child specification with the `Finally` action of the restart intensity set to `kill_sup` and this child reaches the maximum restart intensity, the supervisor applies the `Shutdown` strategy to its children in reverse start order and then it finishes. In the following section we describe how some of these properties were verified using McErlang.

4 Verification using McErlang

To verify the nos_supervisor described in the previous section using McErlang we follow the approach described in Sec. 2.2, i.e., we create a verifiable model, we formulate a number of correctness properties, and we generate a set of scenarios.

4.1 Create the Model

Obtaining the model for this case-study is straightforward since McErlang can use the actual source code as model. In this section we explain the only change to the source code of the nos_supervisor that was needed to obtain a verifiable model. To measure the restart intensity the nos_supervisor needs to determine the number of restarts that took place within a certain time interval. As McErlang currently

implements neither real-time nor discrete-time model checking algorithms we were forced to abstract away from the time interval.

```
add_restart(#child_spec{
    restart_intensity = infinity
    }) -> [];
add_restart(#child_spec{
    restart_intensity = {MaxR, MaxT, Finally},
    state = ChildState}) ->
  Restarts = ChildState#child_state.restarts,
  Now = now(),
  check_restarts( MaxR
                , Finally
                ,filter_restarts(MaxT
                                ,[Now|Restarts]
                                )
                ).
```

As we can see above, the nos_supervisor stores the restart time of each process in a list, which is then filtered using the difference between the time of the current restart and the maximum time specified by the restart intensity. If the resulting list is greater than the allowed number of restarts, then the `Finally` action is triggered. If not, the filtered list with the new restart time is returned:

```
filter_restarts(MaxT, [H | Restarts]) ->
  F = fun(Restart) ->
        difference(Restart, H) < MaxT
      end,
  [H | lists:takewhile(F, Restarts)].

check_restarts(MaxR, Finally, Restarts) ->
  case length(Restarts) > MaxR of
    true -> Finally;
    false -> Restarts
  end.
```

The solution was not to store concrete times when restarting, but merely recording that a restart occurred (using the symbol `now`), until the length of the list containing restart indications is equal to the maximum number of restarts. The last two lines of `add_restart` are thus replaced by the following code fragment:

```
  NewRestarts = case length(Restarts) >= MaxR of
      true  -> Restarts;
      false -> [now | Restarts]
    end,
  check_restarts(MaxR, Finally, NewRestarts).
```

It no longer makes sense to filter the list, but instead the model checker must consider two possibilities: whether these restarts happened within the maximum time or not. McErlang offers the possibility to express such a nondeterministic choice using a function call to `mce_erl:choice` giving the branches as a list of anonymous functions as shown below, and during model checking both alternatives will be explored:

```
check_restarts(MaxR, Finally, Restarts) ->
  case length(Restarts) >= MaxR of
    true ->
       mce_erl:choice([ fun() -> Finally end
                      , fun () -> Restarts end
                      ]);
    false ->
      Restarts
  end.
```

4.2 Formulating Correctness Properties

As explained in section 2.2, in McErlang correctness properties can be specified either using a safety monitor, which run in parallel with the system to verify and observe its actions, or as a formula of linear temporal logic. In practice, most of the relevant nos_supervisor correctness properties can be expressed as safety monitors.

In McErlang a safety monitor is implemented as an Erlang behaviour; a module implementing a safety monitor must implement the following callback functions:

- an `init` function to initialize the monitor (which should return the initial state of the monitor).
- a `stateChange` function: when the model checker computes a new system state, this function is called with the following arguments: (i) the new system state, (ii) the current state of the monitor, and (iii) the sequence of system actions that occurred during the computation of the new system state. The `stateChange` function should determine whether the new system state, and the system actions, are acceptable given the current state of the monitor. If so, the function should return a new monitor state, otherwise a failure reason.

4.2.1 An Example Safety Monitor

In this section, a safety monitor which checks some properties for the nos_supervisor is shown. The relevant properties of interest are:

- a child is spawned only if it has died
- no process is killed by the nos_supervisor without having a sibling process that has terminated too many times (so that it should not be restarted again).

To be able to determine whether a process spawning or a kill action caused by the nos_supervisor is allowed, the monitor has to keep track of the state of all its children. Thus, the state of the monitor is a record keeping track of the status of all child processes under supervision:

```
-record(monitorState,
% List of dead or never started children
% ordered by the crash time
    { deadProcesses = []
% children killed by supervisor
    , killedProcesses = []
% spawned children currently alive
    , spawnedProcesses = []
% number of restarts for children
    , supervisorChildren = []
    , supervisorPid = undefined
    }).
```

The main function of the monitor is depicted below:

```
stateChange(_,MonState,Actions) ->
  ...
  case interpret_action(Action) of
    {died, Pid, normal} ->
      {ok,Monstate};
    {died, Pid, Reason} ->
      died(Pid, Monstate);
    {spawn, SpawnInfo, SpawnedPid} ->
      case SpawnInfo of
        {supervisor, Intensities}
          -> setChildren(Intensities,Monstate);
        {worker, WorkerName}
          -> spawned({WorkerName, SpawnedPid}
                     ,Monstate)
      end;
    {killedby, SourcePid, KilledPid} ->
      killed(KilledPid, Monstate);
     _ ->
      {ok,Monstate}
   end
   ...
```

where the function `interpret_action` splits concrete program actions into different abstract categories, and for each one it checks whether that action is acceptable in the current monitor state. The action `{died, Pid, normal}`, for instance, represents the fact that a process has terminated normally (and so should not be restarted). If the abstract action represent a new child process being spawned, the function `spawned` is called:

```
spawned({WorkerName, Pid}, State) ->
 DeadProcs =
    State#programState.deadProcesses,
 SpawnedProcs =
    State#programState.spawnedProcesses,
 case lists:member(WorkerName, DeadProcs) of
   true ->
     State#programState
     {deadProcesses = lists:delete(WorkerName
                                   ,DeadProcs),
      spawnedProcesses = [{WorkerName,Pid}
                          | SpawnedProcs]};
   false ->
     throw("Already␣spawned␣worker")
 end.
```

The `spawned` functions checks that the (name of the) newly spawned child function is not already spawned, and removes the new child from the list of dead processes and then adds it to the list of spawned ones. If the child is already spawned, an exception is thrown which notifies McErlang that the monitor has found an error.

Similarly, when a child dies abnormally the `died` function is called, which increments the restart counter for the child. This counter is checked when the nos_supervisor kills a child to ensure that a sufficient number of restarts have occurred for some sibling of the killed process.

It is interesting to note the way in which we formulate correctness properties using safety monitors. Instead of specifying them in a temporal logic, what is done is to develop a set of simplified models of the nos_supervisor system, and then check whether the behaviour of the real nos_supervisor corresponds to these models. The use of the same language for regular development and for specifying safety monitors eases the adoption of this technique by the developers.

4.2.2 Checking Liveness Properties.

Some properties, i.e., liveness properties that express claims regarding eventual behaviour, cannot be implemented as safety monitors. In this case, we can instead formulate the property in LTL and use the automatic translator from LTL formulae to Büchi monitors. For example, in the case study an interesting property to check is that always that a child terminates abnormally, it gets eventually restarted.

This property is expressed as:

```
always (P => eventually Q)
```

where `P` and `Q` are predicates stating that *a child terminates abnormally* and *a dead child gets restarted*, respectively. Such predicates are specified in Erlang, and the correspondence between the names in the LTL formula and the concrete implementation must be given to McErlang. As an example of a predicate, this function implements the predicate that states that *a child terminates abnormally*:

```
child_terminated(_, Actions, _) ->
 lists:any
 (fun (A) ->
   try
    died==mce_erl_actions:type(A),
    normal=/=mce_erl_actions:get_died_reason(A)
   catch _:_ -> false end
  end, Actions).
```

As can be seen, a predicate is a function which receives three arguments. The first is the program state, the second are the actions which triggered the state change, and the third is some private state. If any action is an action corresponding to a process dying (`died` action), with a `Reason` different than `normal`, this means that a child terminated abnormally.

Note however, that this property holds only for a nos_supervisor whose children have restart intensity `infinity`; otherwise, after a sufficient number of deaths, the child would not be restarted. To check more complex features, we need to keep a private state, and pass it along between the state predicates (thus corresponding to a monitor state in the generated Büchi automaton).

4.2.3 Modular Safety Monitors

Instead of trying to check all the desirable properties of the nos_supervisor using a single complex safety monitor, it is advisable to define several safety monitors, each checking a particular property of the nos_supervisor. This approach reduces the risk of checking the system with incorrect safety monitors, as the resulting monitors individually are much easier to understand and write. Moreover, a large part of a safety monitor code is reusable when writing a new one. That is, the strategy in which concrete actions are translated into abstract ones and the way the monitor state is updated upon process deaths, spawn and kills, is completely generic. What changes from one safety monitor (property) to another is how the actions are interpreted – i.e., when the occurrence of an action signal is interpreted as an error.

These are some of the safety monitors used in the verification of the supervisor component:

1. **A supervisor will always try to restart a child, until one reaches the maximum restart intensity.** Applicable for checking child specifications with restart intensity different than infinity, and with `kill_sup` finally action.

2. **When a child reaches its maximum restart intensity, living workers are killed in reverse start order and then it terminates.** Applicable for child specifications with restart intensity different than infinity, and with `kill_sup` finally action.

3. **When a child reaches its maximum restart intensity, living workers are stopped in reverse start order.** Applicable for child specification with restart intensity different than infinity with `kill_sup` finally action and `infinity` as shutdown strategy.

4. **If a child has infinity as shutdown strategy, the supervisor never kills it.**

5. **If a child has an integer as shutdown strategy, a supervisor never kills a process before it has tried to stop it.**

6. **When the shutdown strategy for a child is `stop_child`, when the supervisor stops, the workers which were not respawned had reached their maximum restart intensity.**

7. **For the `all` restart strategy, when a child dies, the supervisor kills alive children in reverse starting order.**

8. **For the `all` restart strategy, the workers are restarted in start order after killing all alive children.**

4.3 Verification Scenarios

To verify the nos_supervisor against the above correctness properties using McErlang, a number of scenarios were designed manually, although it should not be too difficult to generate them automatically (e.g., using QuickCheck/Erlang [2]). To create this scenarios, a test worker `nos_test_worker` has been implemented which only keeps track of its starting time. To simulate process crashes, we enable an option in the McErlang model checker which, non-deterministically, kills any process in any state. We select a subset of the running processes for termination by executing:

```
mcerlang:process_flag(do_terminate,
                      true)
```

in any process that is a candidate for termination (in the case study, the worker processes). Thus, a worker processes can non-deterministically die at any moment, which will cause the nos_supervisor to be informed (and hopefully take action).

As an example of a concrete scenario, to check the liveness property *if a child dies then eventually the nos_supervisor will restart the child* the simplest adequate scenario would be a nos_supervisor which spawns a child with restart strategy `child` (the rest of options are not relevant).

```
{worker1,
  {nos_test_worker,start_link,[worker1,foo]},
  {nos_test_worker,restart_link,{worker1,foo}},
  child,
  infinity,
  brutal_kill,
  []}
```

We identified the relevant scenarios as a nos_supervisor with, at least one (two or three depending on the property) child processes. All the child processes in a scenario have the same specification for simplicity.

Each scenario was chosen to verify properties related to the behaviour of the nos_supervisor related to some of its options. For example, if we want to verify that the nos_supervisor evaluates a `Finally` action correctly when a child reaches its maximum restart intensity, we only require a restart intensity different than `infinity`, but we must know if we should expect a `exit(kill)` or a `exit(shutdown)` (which shutdown strategy is being applied).

4.4 The McErlang Debugger

What can be done if a property fails? McErlang provides a tool for exploring counterexamples, manually exploring the state space, ...: the McErlang debugger.

When running the model checker with property *(ii)*, McErlang returns a counterexample, indicating that this property has failed:

```
*** Property violation detected at
    minimum depth 13
*** Monitor failed
monitor error:
{failed_monitor
 ,"Processes not killed in reverse start order"}
Stack depth 13 entries;
    state table contains 44446 states.

Access result using get(result)
To see the counterexample type
    "mce_erl_debugger:start(get(result)). "
...
```

As can be seen, the length of the trace which leads to an error is shown, as well as the concrete scenario of the failure. In the program trace given by the debugger, we realized that the kill order was not the proposed in the specification. The debugger also allows us to manually explore the state space to analyze other paths, and help us to locate the error (under which circumstances does this error arise).

4.5 Experimental Results

The safety monitors previously described were checked on a set of scenarios, constructed as described in Sect. 4.3. We present here some measures taken in a Intel(R) Core(TM)2 Quad

at 2.33GHz with 4GB of RAM memory. Figure 2 shows the number of states explored (Fig. 2a) by the model checker and the time required (Fig. 2b) to check the safety monitor (i) given in Sect. 4.2.3, for a scenario with restart strategy `child`, a restart intensity of {`1,1,kill_sup`}, and different number of workers. The state space may vary depending on scenario parameters (using the same number of workers). For example, the number of states explored by the model checker using {`1,1,kill_sup`}, {`2,1,kill_sup`} and {`3,1,kill_sup`} were 6617, 13656 and 26712, respectively.

As expected with model checking techniques, the state space grows exponentially making difficult to check large scenarios using the actual implementation as a model. Nevertheless, even though nos_supervisor behaviour has been deployed in a number of LambdaStream products and no truly critical errors were expected to be found, surprisingly, one discrepancy between the specification in the component documentation and the actual implementation of the nos_supervisor was found. McErlang returned a counterexample for the following combination of scenario and property *If any children with specification* `kill_sup` *and* `Finally` *reaches the maximum restart intensity and has* `brutal_kill` *shutdown strategy, then the supervisor only kills a child after all the "younger" children (those that have been started after this child) are not running (stopped, killed, crashed, dead, ...)* . The counterexample returned by McErlang was analyzed using the McErlang debugger and it turned out that an "older" worker was killed before a "younger" worker, i.e., they were not killed in reverse start order as it was explicitly stated in the documentation.

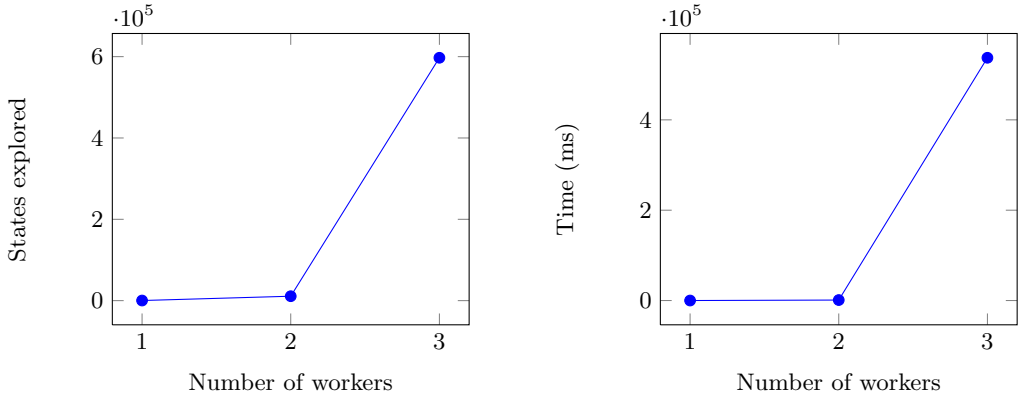
5 Conclusions

In this paper we have explored the verification of safety and liveness properties using the McErlang tool on a process supervisor deployed as part of several real-world products. Thanks to this verification, we have improved the component's reliability, not only because a slight discrepancy between specification and implementation was identified but also because component specification became much more precise. From this verification effort we can conclude that model checking is a valuable technique for analyzing concurrent programs, and that McErlang can be successfully applied to industrial software.

The methodology we have followed consists of three steps (a) creating a model for the component, (b) expressing and implementing the properties of interest, and (c) creating scenarios where the properties were checked. Creating the model is a straightforward task as McErlang can use the source code as a model with minimal changes. In the case study, the only required change was to abstract from the timing aspects of the supervisor, into a nondeterministic choice, as currently McErlang implements neither real-time nor discrete-time model checking algorithms. Even though we have been able to verify most aspects of the supervisor without considering exact timing, an important aspect for future work is to add support for real-time model checking algorithms to McErlang.

The properties of interest were extracted from the component documentation, and from informal discussion with the developers of the supervisor component. Most of the properties were formulated as safety monitors, written in Erlang, which observe the actions of the supervisor component as it manages a set of children, and signaling an error if the supervisor issues an incorrect command. In other words, we have defined a set of simplified models, and check that the real supervisor has the same behaviour as the models (up to the abstraction level of the monitor).

To fight the inevitable state explosion problem of model checking we apply the McErlang model checker not to a large monolithic scenario, but define and check a large number of smaller scenarios (varying, for example, the number of work processes). Even though the verification is partial, as there is no way we can check every possible scenario, we discovered a discrepancy between the documentation and the actual implementation of the component



(a) States explored

(b) Time required.

Figure 2: States explored and time required (restart strategy=`child`, restart intensity=`{1,1,kill_sup}`).

in a small scenario comprised of one supervisor and three children.

A significant advantage of the approach to model checking taken in McErlang, compared to other model checkers, is that there is no need for learning a new specification language since Erlang is both used as a programming language and as a specification language. This is achievable, in part, due to the inherent power of a functional programming language which is sufficiently expressive to be used both for programming and for writing more abstract specifications.

Still obviously there is much room for improvement. The learning curve to be able to use McErlang effectively, and to formulate correctness properties, is currently too steep. In next release of McErlang improvements are planned regarding the usability of the tool, to provide, for example, better information on error causes, guidance in selecting appropriate verification options, and a simplified API for the formulation of correctness properties.

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