Monitoring and Controlling
Distributed Applications Using Lomita*
(Position Paper)

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Over the last four years, we have developed the Meta toolkit for controlling distributed applications. This toolkit has been publically available as part of the academic ISIS release, and has been used both within and outside of Cornell for building various system monitoring and control applications [5, 3, 4].

One major stumbling block with using Meta has been the language (called NPL) it supports. NPL is very low-level and using it is difficult, in the same way it is difficult to write machine language programs or raw Postscript programs. Hence, we have spent the last six months building a higher-level language and runtime environment. Our hope is that with this higher-level approach, we will be able to write more complicated Meta applications and thereby concentrate more on the use (and limitations) of Meta as an architecture.

This note proceeds as follows. In Section 1, we review the Meta toolkit and its intended use. In Section 2 we describe our goals with Lomita and give an overview of its architecture and language syntax. In Section 3 we give a detailed example of the use of Lomita by presenting a complete program for a load-adaptable service.

1 Review of Meta

A reactive system architecture partitions the system into two components: an active environment and an input-driven control program. The control program monitors the state of the environment through a sensor abstraction, and when the state meets some condition then it alters the environment's state through an actuator abstraction. Process control systems naturally have a reactive architecture, as does system and network monitoring, software tool integration, debugging, and automatic system management.

The Meta toolkit assists in the construction of distributed and reliable (albeit non-real-time) reactive systems. With Meta, one can instrument a program with software sensors and actuators in order to expose its state for control. Then, a control program can be written to monitor and control the instrumented programs. The Meta architecture interprets the control program in a distributed manner in order to supply both lower latency and tolerance to partial failures of the environment. Furthermore, the monitoring and control is done in a way to guarantee that the observed global state is consistent and changed atomically with respect to the monitoring of the control program.

For example, consider a simple computation server that accepts jobs and executes them in
the order received (the pending job requests are kept in a queue). The load of a server is the estimated time needed to complete all submitted jobs. As well as being submitted, a job can be cancelled and the server can be stopped (losing all submitted jobs).

This server can be instrumented with a sensor that gives the load of the server and a sensor that gives the queue of submitted jobs. It can also be instrumented with two actuators: one that cancels a job and one that stops the server. Then, Meta can be used to construct a service out of servers—for example, an actuator can be defined that submits a job to the lightest-loaded server of a group of servers, and a sensor can be defined that gives the average load of a set of servers. And, a control program can be written that creates additional servers on lightly-loaded machines when the average load is too high. Section 3 develops this example more fully.

There are two steps to managing a distributed application with Meta: instrumenting the application and writing the control program. Instrumentation is the more straightforward task. A Meta sensor or actuator is simply a procedure that is added to the application, where a sensor has no side-effects and an actuator changes the state of the application and returns success or failure. These procedures are registered with Meta using a library routine, which also associates a name and a type signature with the sensor or actuator. Finally, Meta has a set of library routines that synchronizes the sampling of sensors and invocation of actuators with its own operation in order to guarantee that Meta sees and alters on only locally consistent states.

An instrumented program is an example of a Meta context, that is, a named set of sensors and actuators. In Meta, each context belongs to a single context class that defines the types of its sensors and actuators. For example, if we assume that only one computation server will be run on any given machine, then the load sensor of a computation server running on a machine grimnir could be named serv(grimnir).load, where the context is named serv(grimnir) and is of a context class named serv.

Instrumented programs define what is called in Meta base contexts. Base contexts can be grouped into group contexts1. Put another way, a group context class can be defined as a collection of contexts from the same base context class, and a base context can join and leave any number of group contexts of a compatible class. Each sensor of the base context class exists in the group context class except that the type of the sensor is promoted to a set value. For example, assume that service(t) is a group context class comprised of serv contexts. If the load sensor in the context class serv has an integer type, then service context class also has a load sensor but its type is set of integers. The value of this sensor in some group context is the set of load sensor values, one for each base context that is a member of the group context.

Similarly, the actuation of service(1).stop will actuate serv(x).stop for every serv(x) that is a member of service(1), and the value of the actuation is success if all base actuations succeed; else the value is failure. Actuators in group context classes can also take two additional parameters: a positive integer and a set of values obtained from a sensor of the group. The first parameter specifies a number k of base contexts and the second parameter specifies a preference ranking r of the base contexts indicated by the source of the individual value. The actuation will invoke the actuator on the first k contexts denoted by r. For each that returns failure, an additional context is chosen from r. The group actuation will return success if k base contexts return success. For example, service(1).shutdown(2, sort(load)) will shut down the two lightest-loaded servers that are members of service(1).

Control programs are written in a simple programming language called NPL. An NPL command is equivalent to an atomic guarded command \( \langle \phi_1 \rightarrow \alpha_1|| \ldots || \phi_m \rightarrow \alpha_m \rangle \), where each \( \phi_i \) is a predicate expression over sensor values and each \( \alpha_i \) is a sequence of actuator invocations.

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1 A group context is called an aggregate in Meta. Meta is somewhat confusing in terms of contexts and context classes, however, and so we use the (hopefully clearer) Lomita terminology here.
whose parameters can be expressions of sensor values. The meaning of such a command is that it blocks until some \( \phi_i \) is true, at which point the corresponding \( \alpha_i \) executes, and any effects of \( \alpha_i \) are not visible to other guarded commands until \( \alpha_i \) terminates. Such commands can be one-shot (once an \( \alpha_i \) executes the command terminates) or iterative (once an \( \alpha_i \) executes the command resumes waiting for a predicate to become true). Meta also guarantees that an NPL command observes a valid sequence of global states. That is, not only is each global state used to evaluate a \( \phi_i \) a valid global state [1], but the sequence of states is also consistent with the actual run of the environment [2].

Each context has associated with it an interpreter of NPL commands. For base contexts, the interpreter resides in the same address space as the instrumented program. An NPL command can be run in any interpreter (that is, an NPL program using fully-qualified names can be submitted to any context without changing its meaning), although the latency due to network communication is large—a command may run up to 500 times slower in a remote context than in a local context. Of course, some programs refer to more than one context and so must refer to some remote sensor or actuator no matter in which context they are run.

Interpreters for group contexts are created by informing an interpreter that it should also implement the group context. For example, the interpreter for serv(grimmnir) can be told to also implement the service(1) context. In addition, more than one interpreter can be so informed, in which case they run in a replicated mode—even though an interpreter fails, the context will remain accessible and the NPL commands it is running will continue to run.

2 Lomita

Although Meta is a powerful system, it is extremely awkward to use. The NPL programs one writes for even simple control programs are very hard to read and to validate their correctness. Our goal with Lomita is to provide enough syntax and supporting semantics in order to make Meta usable.

The central idea of Lomita is to fully implement the context class abstraction. Rather than submitting NPL programs to contexts, one writes a description of the context classes which includes a set of atomic commands (in a syntax much more readable than NPL). The Lomita runtime system then ensures that contexts are initialized and recovered with the appropriate NPL commands.

Lomita consists of two parts. First, there is a compiler that takes Lomita programs and produces an object file. Second, there is a replicated fault-tolerant service called the Lomita runtime that, when given a Lomita object file, loads the file into an internal database. The runtime monitors the currently active contexts and downloads the relevant NPL commands from its internal database when necessary. The runtime also creates interpreters for group contexts when they are needed.

A Lomita program consists of a set of context class definitions. Each context class definition specifies the attributes of the context class and lists the rules to be run in each context of that context class. Attributes can either be Meta sensors or actuators, they can be functions or they can be the Lomita key construct.

The example in Section 3 gives several context class definitions. For example, the definition of the machine context declares that there is an instrumented program that supplies sensors on the load of the machine and on who is logged in, and extends this context class with some additional sensors, such as when the machine is to be considered "busy". The definition also contains a single rule that initializes a value by invoking the "stop_server" actuator.

There are three different kinds of context classes that can be declared in a Lomita program: the global context class, base context classes, and group context classes. Each context class defines a set of attributes and rules that apply to all contexts of that class. Base context classes and group context classes correspond with their equivalent in Meta. The global
context class contains a single context, called the global context. The attributes defined in the global context are available in all contexts. For example, every context has its own print actuator, and so print is defined as an actuator of the global context.

Lomita rules has the following syntax:

```plaintext
if/when predicate expression
    do sequence of actuator invocations end
[else if/when predicate expression
    do sequence of actuator invocations end]
```

By default, a Lomita rule is translated into an iterative guarded command, but a programmer can stop iteration by using the exit actuator. The difference between "if" and "when" corresponds to whether the action is enabled in any state satisfying the predicate expression or only in a state in which the predicate becomes true. For example, the Lomita rule

```plaintext
when "marzullo" in login
    do print("watch out!") end
```

prints the message "watch out!" once after each time "marzullo" logs in, while the rule

```plaintext
if "marzullo" in login
    do print("watch out!") end
```

continuously prints the message "watch out!" as long as "marzullo" is logged in.

Group context classes can also specify rules that are to be run in the base context of all members of a group. Such rules are specified by a with statement, which has the following syntax:

```plaintext
with expression/all
    [select when predicate expression /
     remove when predicate expression /
     rule ]* end
```

The expression following the with keyword is called the key expression and when evaluated in the base context, yields the value of the key associated with the group context. A select statement generates a rule for joining the group and remove generates a rule for leaving the group. For example, consider the following definition of a group of machines:

```plaintext
free_machines: machine group
attributes
    key gp: string
end
with type
    select when ! busy
    remove when busy
    if timer(10000)
    do print(name, 
    " has been free for 10 seconds.")
    end
```

The key for the group is the value of the type sensor, which yields the type of instrumented machine. Hence, this context class partitions machines into group contexts all containing the same type of machine. The rule in the with statement is run in each machine context that is a member of a free_machines context—in this case, a free machine will print every ten seconds that it is a free machine.

3 Example

The following is a complete Lomita 1.0 program. The program serv services a simple request for computation (the computation is given a name and an estimated amount of time). An instrumented server is a member of the context class serv, and the context is named by the machine it runs on (e.g., serv(ydalir)). Servers are grouped into two groups—the group of all servers, and the group of servers that are not overloaded (called free_servers). Furthermore, the new actuator add1 defined in free_servers submits a job to the lightest-loaded free server.

A set of rules, associated with the group of all servers, governs the number of server replicas. These rules specify that the number of replicas must be between min_rep and max_rep. Furthermore, if the average load of the servers is too high, then a new server is created, and if the average load of the servers is too low and there is a server with no jobs, then that server is deleted.

```plaintext
#define high_load 5.0
#define max_users 2
```
#define dally 30
#define max_load 30
#define min_load 2
#define max_rep 5
#define min_rep 1
#define serv_cmd "/usr/meta/utils/serv &"
#define has_server get1
#define set_has_server set(1, TRUE)
#define set_no_server set(1, FALSE)

#define wait_new_size get1
#define set_new_size set(1, TRUE)
#define reset_new_size set(1, FALSE)
#define last_nservers get2
#define set nservers set(2, hum_servers)

/* all machines that aren't busy */
freemachines: machine group
attributes
key not_needed
sensor mean_load: real:= avg(load)
sensor num_freemachines:= size( alive )
actuator start_server (number: integer, pref: any)
end
with all
select when ! busy
remove when busy
if timer(dally*1000)
do print( name,
" has been free for ",
dally, " seconds.") end
end

/* all servers that aren't overloaded */
/* actuator add submits job to lightest */
/* loaded server. */
freeservers: serv group
attributes
key not_needed
sensor num_freeservers:= size( alive )
actuator add (number: integer, pref: {integer},
job_name: string, job_time: string)
actuator add1 (jname: string, jtime: string):=
add (1, sort(load), jname, jtime);
end
with all
select when ! overload
remove when overload
end
end

global attributes
sensor get1: boolean
sensor get2: integer
function avg (any): any
function sort ({any}): {any}
function timer (integer): boolean
function select_eq_int ( {integer}, integer): {integer}
actuator exit
actuator set (integer, any)
actuator print (any)
actuator shell (any)
end

machine: base
attributes
key name: string
sensor load: real
sensor alive: boolean
sensor queue: {string}
sensor overload: boolean:=
  load > max_load
actuator add (job_name: string, job_time: string)
actuator remove (job_name: string)
actuator shutdown
actuator stop:= shutdown;
machine(name).stop_server
end
end

if true do stop_server; exit end
df end

tactuator addl (jname: string, jtime: string):=
  add (1, sort(load), jname, jtime);
end
with all
select when ! overload
remove when overload
end
end

end

end

/* All servers. Create a server if the */
/* average load is too high, and destroy */
/* an idle server if the average load is */
/* too low. */

servers: serv
group
attributes
  key not_needed
  sensor num_servers:= size(alive)
  actuator add (number: integer, pref: {integer},
    job_name: string, job_time: string)
  actuator stop (number: integer, pref: {integer})
end

with all select all end

if true do set_new_size; exit end
when num_servers <> last_nservers
do set_nservers; set_new_size end

if wait_new_size
  && (freemachines.num_freemachines > 0)
  && (num_servers <= BOTTOM
      || num_servers < min_rep
      || (avg(load) > max_load
          && num_servers < max_rep))
do freemachines.start_server(1, sort(load));
  reset_new_size end

if wait_new_size
  && (num_servers > max_rep
      || (avg(load) < min_load
          && num_servers > min_rep))
do stop(1, select_eq_int(load, 0));
  reset_new_size end
end

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References