Translating Multi-device Task Models to State Machines

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Abstract: This paper presents an approach for translating multi-device task models to a distributed execution model based on state machines. We consider an expressive extension to ConcurTaskTrees, called multi-device ConcurTaskTrees (MCTTs) as a modeling language for distributed multi-device applications. We use the device labeling operators *Any* and *All*, which specify if user interactions at runtime shall take place on one or all of a set of devices and extend the translation algorithm for "classical" CTT operators with translation rules for these multi-device operators in a distributed setting. Our algorithm exploits concurrent and hierarchical state machines for the execution and the concept of partial state machines during the translation.

1 INTRODUCTION

With the increasing number of hardware and software platforms, model-driven software-engineering methods have become a widely used tool in systems development. In this paper, we focus on the model-driven design of applications which offer users interaction possibilities with multiple devices in a distributed setting. A common tool for model-based design of interactive applications are *ConcurTaskTrees (CTTs)* (Paternò, 2000), which model how activities can be performed in an interactive application and describe relations between the distinct tasks on an abstract level. CTTs as such however do not cover distributed execution of tasks, only annotations of devices to tasks are possible in some implementations, see e.g. (Paternò et al., 2010). Several researchers have considered such "multi-device applications", which connect multiple devices to work collaboratively at the same time, e.g. (Chmielewski, 2014; Rädle et al., 2015). One approach which also considers dynamic task allocation at runtime is *Multi-Device ConcurTaskTrees (MCTT)* (Prehofer et al., 2016). MCTTs introduce new tree operators *Any* and *All*, which specify how tasks can be mapped to devices. Furthermore, they specify user interactions which might occur on several devices during runtime in a flexible way. With *Any*, a (complex) interaction can take place at one of multiple devices, while *All* requires an interaction to take place at all specified devices. The *All* operator is often used for output actions which shall take on all devices, while *Any* can be used to select an input device at runtime. Clearly, this requires a significant amount of runtime coordination among devices as each subtree of a MCTT can be labeled in this way.

It has been shown that CTTs can be translated into efficiently executable state machines (Wagner and Prehofer, 2016; Wagner, 2015), which preserve the defined semantics of the CTT operators (Wagner and Prehofer, 2016). In this paper, we extend this translation to the multi-device case by introducing translation rules for the MCTT operators. These state machines might be used to control (distributed) user interfaces or even whole devices.

2 MULTI-DEVICE TASK MODELS

Multi-Device CTTs (Prehofer et al., 2016) extend classical CTTs by means of two new operators, namely *Any* and *All*, which are called device labeling operators and are used for specifying devices within a MCTT. These operators primarily attach a list of device identifiers to a CTT, a subtree within a CTT or a single task. A device in this context may be a physical or logical entity, with input and/or output capabilities and the ability to execute some kind of logic.

While the original CTT operators (e.g. *En-*

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Table 1: Overview of CTT operators and the MCTT extensions.

Operator	Symbol	Definition
$Ch(\alpha_1,\alpha_2)$	[]	**Choice:** One of the two choices is taken at run time.
$Co(\alpha_1,\alpha_2)$	|||	**Concurrent:** CTTs α_1 and α_2 are performed concurrently, with any interleaving of sub-tasks.
$Di(\alpha_1,\alpha_2)$	[>	**Disabling:** The CTT α_1 is executed and can be interrupted at any time by α_2. Execution continues in α_2.
$En(\alpha_1,\alpha_2)$	>>	**Enabling:** The CTT α_2 starts after the CTT α_1.
		MCTT Extension
$Any^{c_1,\ldots,c_i}(\alpha)$	$Any(\ldots)$	**Any:** The CTT α is executed on one of the devices $c_1,\ldots,c_i$.
$All^{c_1,\ldots,c_i}(\alpha)$	$All(\ldots)$	**All:** The CTT α is executed on all of the devices $c_1,\ldots,c_i$.

abling, *Disabling* or *Choice*) describe a set of possible sequences of basic tasks to achieve the overall goal (Brüning et al., 2008), device labeling operators introduce a spatial domain into the task model (Prehofer et al., 2016). This is achieved due to dynamic assignment of tasks to an arbitrary subset of devices at runtime. The operators *Any* and *All* hereby define the execution semantics, i.e. if a task or task configuration should be executed mutually exclusive on one device (*Any*) or in parallel on several devices (*All*).

MCTTs are best suited for distributed scenarios where a set of tasks should be executed on a multitude of devices. A unique characteristic of the MCTT notation is that it treats device labeling operators just like regular CTT operators. Thus, they can be placed arbitrarily within the task tree. In particular, this also allows for nesting these operators. This is especially useful in cases where arbitrary devices can be selected for the execution of a complex task set, but one or more sub task(s) must always be mapped on a specific device (this is then called a *device labeling exception* (Prehofer et al., 2016)).

The MCTT notation preserves the task types of CTTs as introduced in (Paternò, 2000). It supports *User tasks*, which are cognitive/perceptive and don't require interaction with the system, *Interaction tasks*, which describe any kind of user interaction, e.g. providing inputs or clicking a button and *Application* or *System tasks*, which the system performs without any additional user interaction. *Abstract tasks* are supported as well.

Table 1 shows the CTT operators used throughout this work as well as the device-labeling operators.

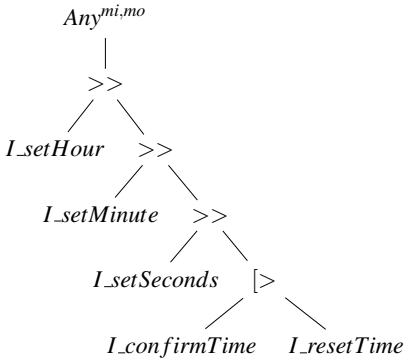


Figure 1: Example of a simple (binary) MCTT for configuring a timer.

For the purpose of this paper, we only use the shown subset of the CTT notation.

An example of a MCTT can be found in Figure 1. It describes how a user would configure an alarm clock, e.g. for a microwave with an additional remote device like a smartphone app. The surrounding *Any* operator defines two devices *mi* (microwave) and *mo* (mobile device). According to the semantics of *Any*, the configuration process can either be started on *mi* or *mo*, but once started on one device, it must also be finished on the selected device.

3 TRANSLATION TO STATE MACHINES

The translation of MCTTs into state machines is based on the recursive algorithm for CTT translation presented in (Wagner and Prehofer, 2016). This algorithm is based on so-called *Partial State Machines (PSMs)*. These are captured as *Connectables* and a connect operator to compose them. We use translation rules for the "classical" CTT operators to corresponding PSMs as detailed in (Wagner, 2015). For instance, an *Enabling* operator is defined as a concatenation of the corresponding partial state machines for its subtrees α_1 and α_2. Contrarily, a *Choice* operator is defined as the union of its subtrees' PSMs. *Disabling* and *Concurrent* operators are basically mapped to hierarchical and concurrent (parallel) states which in turn will be used for subsequent transformations. For a detailed and formal definition of these concepts we refer to (Wagner and Prehofer, 2016) and (Wagner, 2015).

The novelty in this work is the distributed device setting, which requires coordination and synchronization among devices. Therefore, we assume a model where all devices are fully synchronized and aware of the status of other devices. For this purpuse, we

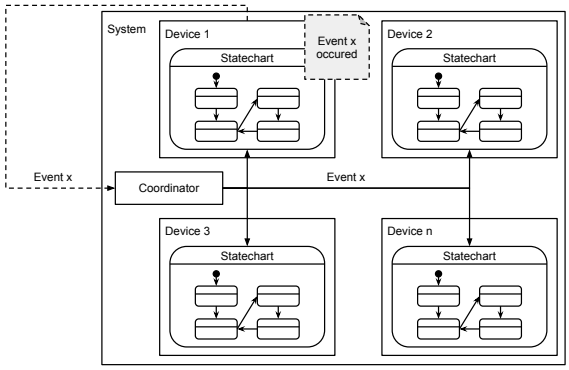


Figure 2: The global system execution model which is assumed for the state machine generation.

generate a state machine for each device which reflects the global system state. This means that the state machine for a specific device also includes states and transitions for all the other devices in the system. These "shadow devices" are used for coordination during a local device's idle phase while other devices are active.

Due to our distributed execution, the implementation of *Any* and *All* needs to use and generate implicit information about required notifications. A notification is basically implemented as a state transition in the generated state machines and its concept is based on a global execution model which is depicted in Figure 2. The basic idea is, that the state machine of each device whose label is present in the label set of an *Any* or *All* operator, also is aware of and follows all states and transitions which are actually executed on other devices. This implies that all events that might occur on any of the defined devices result in state changes on all involved state machines.

Further, we assume a central coordinator where all communication between devices is routed over. If an event is generated on a device (e.g. because the user executes an interaction task), the device forwards the event to the coordinator. The coordinator broadcasts the event to all other state machines in the system. If two devices emit events simultaneously, the coordinator decides about the event to be broadcasted. Consequently, an event will lead to a state transition in every state machine and the *Any* and *All* operators are executed synchronously on all involved devices.

In the formalization below, the translation will have the two new parameters *physical target* and *virtual target*. The *physical target* is the device we actually want to create the state machine for. Consequently, this parameter won't change during the translation run for an actual device. Contrarily, *virtual target* reflects the aforementioned "shadow devices" and might change during the translation (e.g. if the algorithm handles subtrees which are defined to be executed on remote devices). Initially, *physical target* and *virtual target* are equal.

For simple tasks, we reuse the translation rules described in (Wagner and Prehofer, 2016). Consequently, an application task will always be translated into a **basic state** with a so-called *notification transition* appended. Accordingly, interaction tasks will always be translated into **transitions**.

However, because of the semantics of *Any* and *All* operators, we can no longer assume one-to-one relationship between the task and the generated state machine element as it is in a non-distributed environment. Thus, in order to make states and transitions uniquely identifyable, we add a device label to the transition or state. For transitions, we always append the *virtual target* to the transition's event name. For instance, if we want to translate an interaction task "pushButton" which should be executed on a device x (because the task was labeled with e.g. Any^x), the resulting transition would have the event name $pushButton\_x$. The actual value of "virtual target" is determined by the translation rules for the device labeling operators *Any* and *All*, which we will show later in this section.

The translation of application tasks must be modified as well. The main issue here is that we have to distinguish whether or not the task is available on the current device. In any case, we have to create a basic state with a notification transitition attached. The state name itself depends on the current *virtual target*. If it is equal to the *physical target*, we know that the task must be executed locally and thus create a state called "$< taskname\_virtualtarget >$".

If the *virtual target* is different from the *physical target*, we know that the current device has to wait for the completion of the task on a remote device. We therefore have to put the state machine in an idle state. We call these idle states *nop* states, which indicates that these states do not execute tasks ("no operation"). We know that when the state machine of a device is in *nop* states, at least one other (remote) device performs a task at the same time. In order to be able to leave the *nop* state, we attach a notification transition named "$< taskname\_finished\_virtualtarget >$". If this event occurs, the local device knows that the remote device has finished task execution and its local state machine can move on.

As an example, consider an application task "senseTemperature" which should be executed on device x (e.g. the task was labeled with Any^x, so x is the current *virtual target*). The state machine is created for x, which makes x the current *physical target*. Consequently, the generated state has the

form “senseTemperature_x” with an outgoing transition “senseTemperature_finished_x”.

If we create the state machine for device *y* (which would then be the *physical target*), the resulting state would be “nop_y” with an outgoing transition “senseTemperature_finished_x”. Note that this translation schema might lead to many *nop* states within a state machine. In order to avoid naming conflicts, we add additional unique IDs to each *nop* state’s name.

3.1 Translation of Device Labeling Operators

The device labeling operators provide information on which devices tasks are to be executed. The *Any* operator followed by a task subtree α is defined to execute the subtree on one **and only one** of the given devices. If the subtree was entered by one of the defined devices (e.g. device *x*), the other devices defined within the context of the operator are not allowed to perform tasks until the subtree was fully executed by *x*, or until another device (e.g. *y*) must be activated due to a labeling exception defined for *y*.

From a semantical point of view, *Any* is similar to a *Choice*, but with an arbitrary number of alternatives (i.e. the number of labels *Any* is annotated with). As an example, consider Figure 3. A MCTT consisting of three tasks which are connected via *Enabling* operators is labeled with $Any^{x,y}$. This leads to two possible execution paths. Either “clickButton” is executed on device *x*, then, “timerCountdown” and “alarm” must also be executed on device *x* and device *y* must not perform any of the tasks. Option two requires “clickButton” to be executed on device *y*. Then, “timerCountdown” and “alarm” must also be executed on device *y*, but device *x* must not perform any of the tasks. Considering device *x*, the MCTT in Figure 3 thus acts as a *Choice*. Either “clickButton” is executed locally, which implies that subsequent tasks must also be executed locally, or “clickButton” is executed by device *y*, which implies that *x* must neither execute “clickButton” nor any of the other subsequent tasks.

However, one has to decide what device *x* is expected to do when “clickButton” occurs on device *y*. One possible solution (which is also employed by our translation rule) is, that *x* simply follows the execution of *y* but does not execute tasks locally. Instead, it enters representational states (*nop* states) and performs representational transitions which correspond to the actual execution on device *y*. Figure 5(a) and Figure 5(b) show this behavior for the MCTT in Figure 3 by means of partial state machines. One can recognize that states and transitions for both *x* and *y* are always

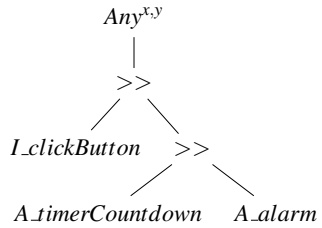


Figure 3: MCTT representing an *Any* operator without labeling exceptions.

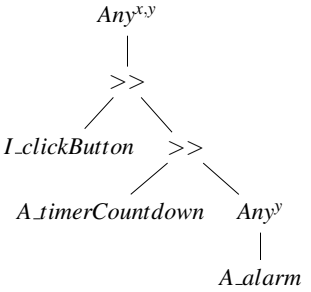


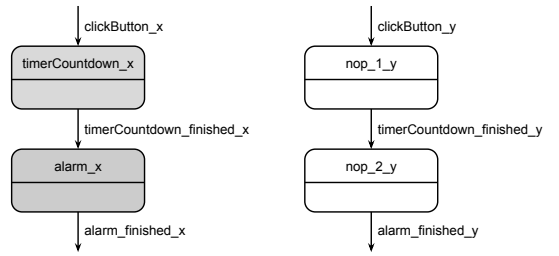
Figure 4: MCTT representing an *Any* operator with labeling exceptions.

part of both devices. However, events and state names depend on the selected execution path. For example, if “clickButton” was chosen on device *x*, *x* follows the gray colored path, whereas *y* follows the white colored path. White states on *y* are only *nop* states, as *y* must not execute task-related functions.

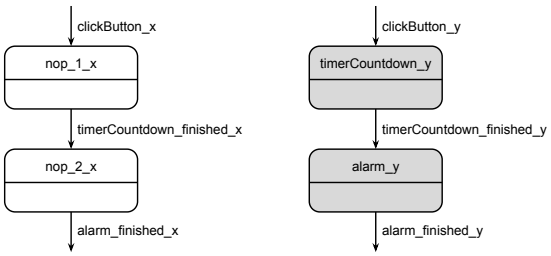
Similarly, we can treat labeling exceptions in a MCTT. For example, let’s assume that the task “alarm” must always be executed on device *y*, even if previous tasks were executed on device *x*, i.e. the MCTT has a subtree $Any^{y}(alarm)$ (Figure 4). Again, we have two possible execution paths. Option one requires “clickButton” to be executed on device *x*. Then, “timerCountdown” must also be executed on device *x* but “alarm” must be executed on device *y*. Option two implies that “clickButton” is executed on device *y*. Then, “timerCountdown” and “alarm” must also be executed on device *y*.

The resulting partial state machines are shown in Figure 5(c) and Figure 5(d). In this case, the PSM for device *x* does not have a state with name “alarm_x” but only a *nop* state. This ensures that the task “alarm” is never executed on *x*. Instead, the PSM for *y* has the state “alarm_y” in both of its execution paths. This ensures that the task’s associated implementation is always executed on *y*, even if “clickButton” was initially performed on device *x*. Note that both devices communicate by the exact same events.

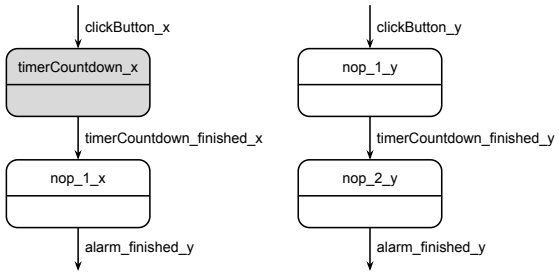
The formal steps of translating an *Any* operator are shown by algorithm 1. Note that we reuse existing translation rules for simple tasks and CTT translators. The *Any* translation orchestrates this by gener-



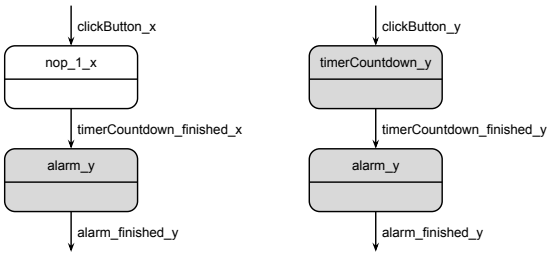
(a) Device *x* without labeling exception.



(b) Device *y* without labeling exception.



(c) Device *x* with labeling exception.



(d) Device *y* with labeling exception.

Figure 5: Concept of "nop" states in partial state machines. White states are never actually executed on the local device. Instead, they act as synchronization points during state machine execution.

ating distinct PSMs for each of its defined labels and returning a merged PSM as result. Lines 8 to 13 iterate over all defined labels of the *Any* operator and generate a PSM for the current label by applying the translation function f to the subtree α. During this step, the *virtual target* parameter is set to the device label belonging to the current iteration. The algorithm then knows whether tasks must be executed locally or will be executed remotely. Consequently, it can generate correctly annotated (*nop*) states and transitions.

Finally, a container PSM_{Any} must be created (lines 14 to 18), which explicitly specifies the input and ouput events of the PSM (see (Wagner, 2015) for details). The *in* set, *out* set and *states* set of PSM_{Any} consist of their merged counterparts of all generated PSM_l.

3.1.1 All Operator ($All^{c_1,\ldots,c_n}(\alpha)$)

The *All* operator enforces execution of the subtree α on **all** defined labels/devices. This requires synchronization at the end of α, so it may only be fully executed if all involved devices reach one of the tasks contained in $last(\alpha)$.

The *All* operator is translated similar to the *Concurrent* operator (see (Wagner and Prehofer, 2016)). The basic idea is that the *All* operator is translated into a concurrent state with a (hierarchical) substate for each label defined in the label set L of the operator. One of these substates represents the actual execution on the current device, the other ones are acting as

Algorithm 1: Translation of the *Any* Operator.

```
1:  function F(mctt, virtual target, physical target)
2:    if mctt is Any(α) then
3:      // initialize sets for result PSM container
4:      inConnectables, allStates, outStates ← ∅
5:      allStates ← ∅
6:      outStates ← ∅
7:      // Build PSM for α for each label
8:      for all l ∈ labels(mctt) do
9:        PSM_l ← F(α, l, physical target)
10:       inConnectables ← inConnectables ∪ in(PSM_l)
11:       allStates ← allStates ∪ states(PSM_l)
12:       outStates ← outStates ∪ out(PSM_l)
13:     end for
14:     create PSM container PSM_Any
15:     in(PSM_Any) ← inConnectables
16:     out(PSM_Any) ← outStates
17:     states(PSM_Any) ← allStates
18:     return PSM_Any
19:   end if
20: end function
```

"shadow devices" (or proxy machines) for the remote execution. These proxies perform only *nop* states (just like for the *Any* operator, but concurrently and not mutually exclusive). We use these proxies, because the concurrent state representing the execution of *All* may only be in its own final state if all remote state machines have reached one of their final states as well, i.e. they executed a task of the *last* set of α. Due to our execution model, we can recognize such remote events and advance the local proxy state machines accordingly. Thus, every concurrent proxy substate is

aware of the global system state.

In order to be able to detect every single event in the *first* set of α, the algorithm must create a state configuration for each possible way of entering α. Similar to the translation of the *Concurrent* operator, we achieve that by creating several concurrent states (one for each label), where each of the concurrent states in turn contains a hierarchical (proxy) state for each label. Altogether, this leads to a total number of n^2 hierarchical states, where $n = |labels(All)|$.

We explain the necessity of generating n^2 hierarchical states by means of an example. Let's assume a simple configuration with two tasks "TaskA" (interaction task) and "TaskB" (application task) which are connected with an *Enabling* operator. The whole tree is labeled with $All^{x,y}$. According to the semantics of *All*, both "TaskA" and "TaskB" must be executed by device *x* and device *y* concurrently.

Intuitively, we would generate only one concurrent state with *n* hierarchical sub states - one for *x* and one *y*. However, Figure 6(a) shows a problem (i.e. a race condition) which will occur during runtime. Let's assume we observe device *x* during execution and "TaskA_y" is the first event that is detected by *x*. Then, the PSM of *x* will enter the concurrent state via transition "TaskA_y". Now "TaskA_x" cannot be recognized anymore and the execution semantics of *All* is violated.

The solution for this problem is to generate n^2 hierarchical states instead, which is depicted in Figure 6(b). Because there are two concurrent states which have unique ingoing transitions, both events "TaskA_x" and "TaskB_y" can be processed independently. For example, if event "TaskA_x" was sensed by device *x* first, the state machine enters $Parallel_1\_x$. From there it is still possible to process the event "TaskA_y" and we preserve the semantics of *All*.

The formal translation steps of the *All* operator are shown by algorithm 2. To create concurrent states with hierarchical proxy states for each label, the algorithm performs a nested loop over the labels of the *All* operator (lines 6 and 9). Within the nested loop, the algorithm creates partial state machines $PSM_{sublabel}$ by means of the translation function f. Thus, we reuse already existing translation rules for basic tasks and CTT operators (and also nested *Any* operators). Note that PSMs are always created for the current label of the inner loop (line 10). This ensures that states and transitions are created with the right labels (i.e. *virtual targets*), so that they represent the corresponding device correctly.

In the next step, the algorithm decides if the entering transitions must be extracted or encapsulated in a hierarchical state. The decision is based on the label variables of the outer and inner loop (line 11). If the labels are equal, the entering transitions will be extracted and later used as ingoing transitions for the concurrent state. For this purpose, $PSM_{sublabel}$ is equipped with final states, resulting in $PSM_{sublabel_{final}}$. From $PSM_{sublabel_{final}}$, all transitions of the *in* set are extracted. The rest of $PSM_{sublabel_{final}}$ is wrapped into a hierarchical state and saved together with the ingoing transitions (lines 13 to 17).

If the labels are not equal, the entering transitions will not be extracted but encapsulated in a hierarchical state. This results in a new state machine $PSM_{sublabel_{exec}}$. $PSM_{sublabel_{exec}}$ is then wrapped into a hierarchical state and saved (lines 18 to 22).

When all labels of the inner loop are processed, a concurrent state *P* is created, which contains all hierarchical states built during the inner loop. *P* is then equipped with a completion transition (i.e. a transition which we expect to be called by the runtime as soon as all hierarchical states have reached a final state) and saved together with ingoing transitions of its hierarchical states (lines 25 to 30).

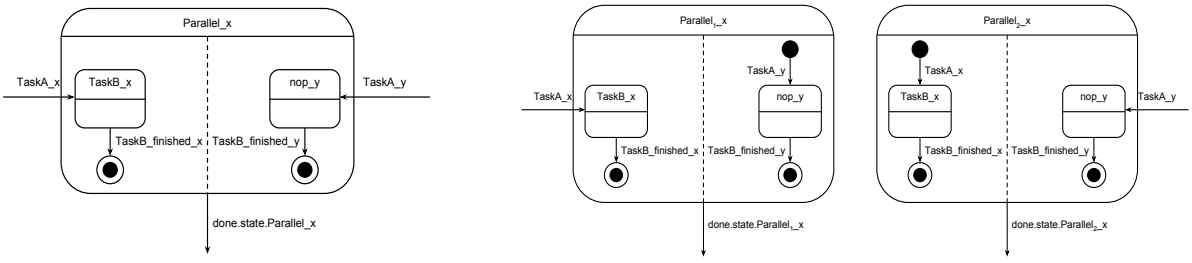
The result of the outer loop is a set of concurrent states, with each concurrent state having a set of ingoing transitions. These concurrent states, their ingoing transitions and their completion transitions are returned as resulting PSM_{All} (lines 32 to 35).

3.2 Example

We show the applicability of the presented approach by a simple alarm system. It can be configured by both a hardware appliance (in the following denoted as *hw*) and a smartphone (in the following denoted as *sp*). The hardware device takes care about all the sensing and surveillence. If it detects anything malicious, an alarm should be raised on all devices, i.e. both the hardware device and the smartphone. The alarm must then be confirmed on all devices.

The MCTT for this application is shown in Figure 7. It presents the basic structure of the system, including all the possible tasks and their relations. The whole configuration is annotated with an *Any* operator to indicate that the setup can be started by either the smartphone or the appliance. However, only the appliance can perform the sensing part, thus we annotate the task with a *labeling exception* Any^{hw}. If the sensing task is finished[2], the system should execute an alarm task. We assume the alarm task to be infinite, so we wrap it into a *Disabled* operator to be able to cancel the task. The whole alarm subtree is labeled

[2]We don't provide any details here on *when* or *how* the sensing task is finished. This remains for to the actual implementation.



(a) (b)

Figure 6: In order to preserve the execution semantics of *All*, n^2 hierarchical (sub) states must be created, where n is the number of labels *All* is annotated with (PSMs were created for device x).

Algorithm 2: Translation of the *All* Operator.

```
1: function F(mctt, virtual target, physical target)
2:   if mctt is All(α) then
3:     inConnectables, allStates, outConnectables ← ∅
4:
5:     // Build a separate parallel state for each label
6:     for all label ∈ labels(mctt) do
7:       inTransitions, compounds ← ∅
8:       // Build proxy compound states
9:       for all sublabel ∈ labels(mctt) do          ▷ Build PSM for α
10:        PSM_sublabel ← F(α, sublabel, physical target)
11:        if label = sublabel then
12:          // Extract ingoing transitions
13:          PSM_sublabel_final ← CreateFinalStates(PSM_sublabel)
14:          transitions_sublabel ← transitions of in(PSM_sublabel_final)
15:          C ← Compound(states(PSM_sublabel_final), sublabel)
16:          compounds ← compounds ∪ {C}
17:          inTransitions ← inTransitions ∪ transitions_sublabel
18:        else
19:          // Pack into compound state with ingoing transitions
20:          PSM_sublabel_exec ← CreateExecutionClosure(PSM_sublabel)
21:          C ← Compound(states(PSM_sublabel_exec), sublabel)
22:          compounds ← compounds ∪ {C}
23:        end if
24:      end for
25:      P ← ParallelState(parname, compounds, physical target)
26:      t_completion ← Transition("done.state. < parname >", physical target)
27:      P --connect--> t_completion
28:      allStates ← allStates ∪ {P}
29:      outConnectables ← outConnectables ∪ {t_completion}
30:      inConnectables ← inConnectables ∪ inTransitions
31:    end for
32:    create PSM container PSM_All
33:    out(PSM_All) ← outConnectables
34:    states(PSM_All) ← allStates
35:    return PSM_All
36:  end if
37: end function
```

with $All^{sp,hw}$ in order to indicate that both the alarm and the confirmation must occur on all devices.

The resulting state machines for both devices *sp* and *hw* are depicted in Figure 8. One can observe that the state machine for device *sp* includes *nop* states for the labeling exception $Any^{hw}(sense)$. Thus, *sp*

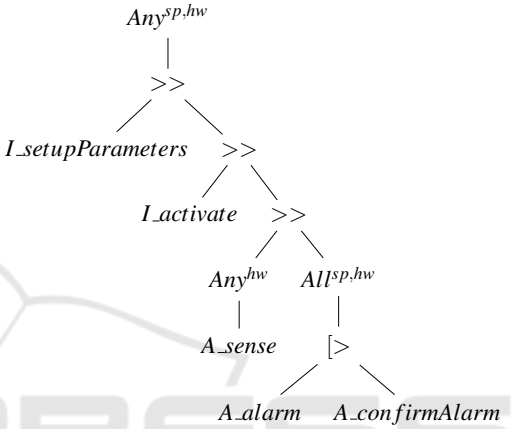
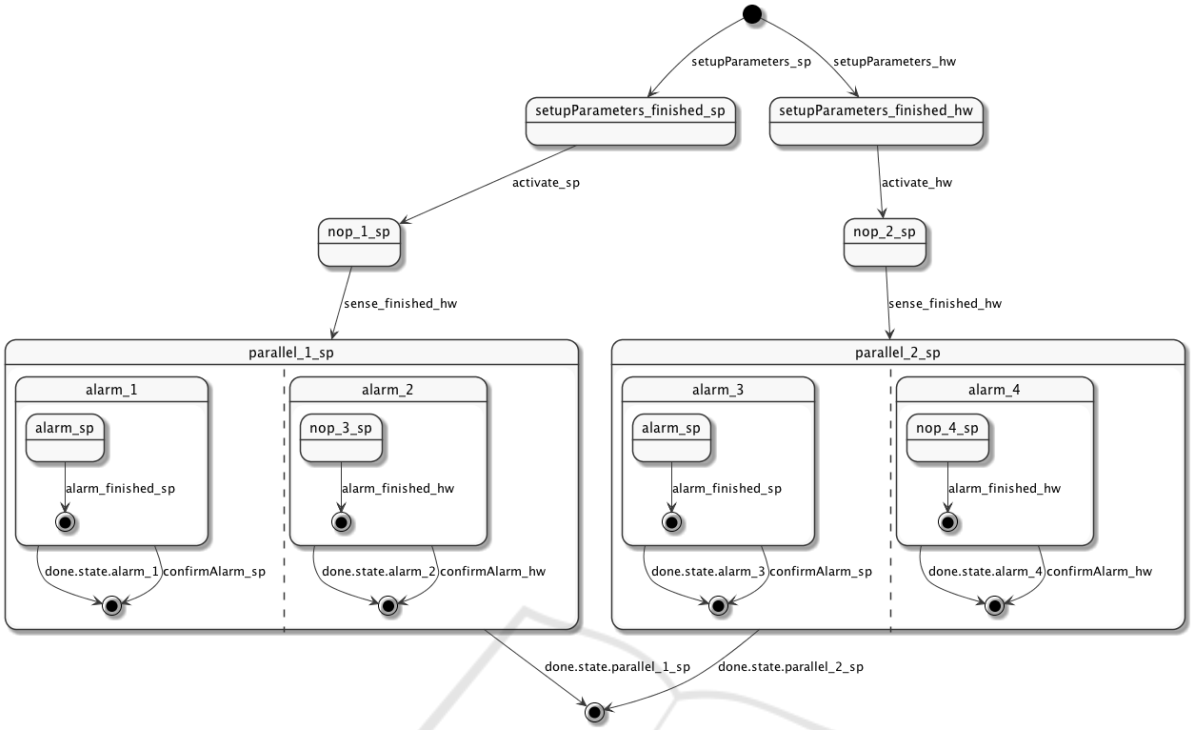


Figure 7: The MCTT of the alarm system example.

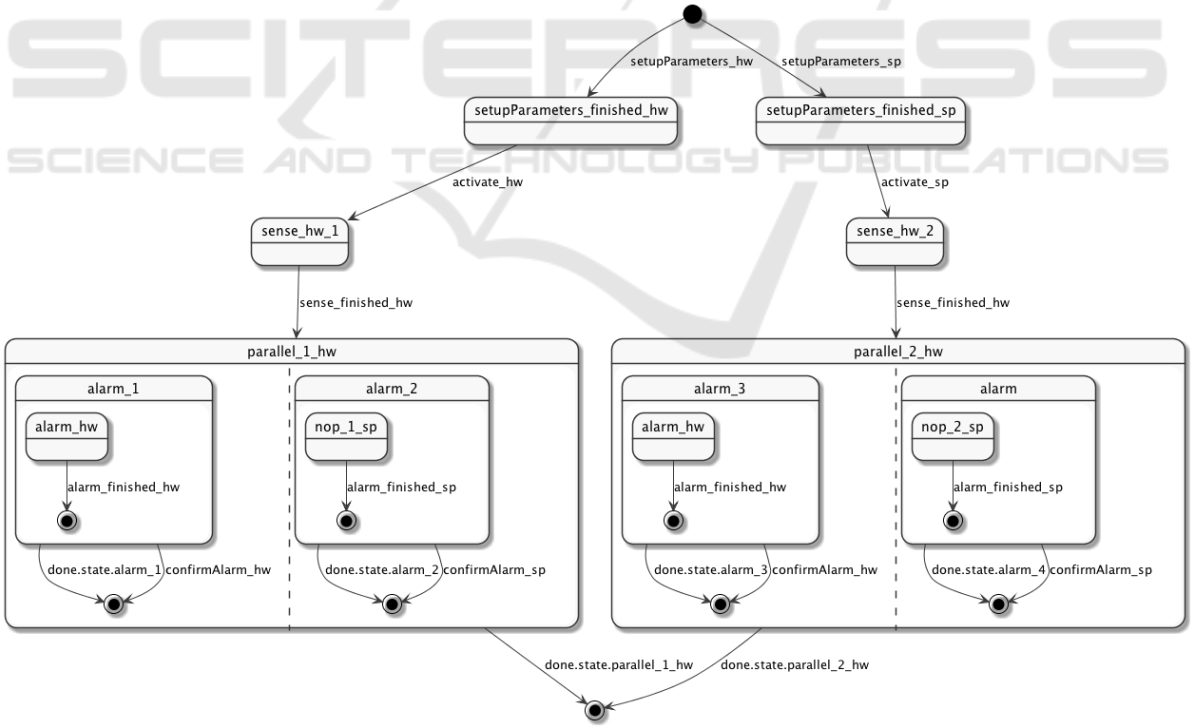
is in an idle state while device *hw* is in the *sense* state. *sp* will wake up as soon as it detects the event *sense_finished_hw*. Note that it doesn't matter if the *setupParameter* and *activate* tasks were executed on *sp* or *hw* - the wakeup of *sp* is guaranteed in any case.

Another aspect of the translation which we want to explain in more detail is the result of the subtree labeled with $All^{sp,hw}$. For both devices, our algorithm generates two concurrent states (one for each possible execution paths). Within a concurrent state, we have a hierarchical state for each device in the device set of the *All* operator. Depending on the actual device we created the state machine for, we have different *nop* state combinations. For example, the hierarchical states on device *sp* have *nop* states for *alarm* states of device *hw* and vice versa. In principle, *sp* is only interested in notification events from *hw* in order to synchronize the state transitions.

This example clearly presents the essence of our approach: The state machines of all involved devices are executed in a completely synchronized manner. Thus we can achieve a distributed, but coordinated execution of the desired system behavior, which in turn preserves the defined semantices of both CTT and labeling operators.



(a) State machine for device *sp*.



(b) State machine for device *hw*.

Figure 8: Generated state machines for the alarm system example.

4 RELATED WORK

Task models are often used for model-based user interface development (MBUID), and many researchers have investigated how task models support multi-device applications development in ambient intelligence environments. E.g. the work in (Paternò et al., 2010) exploits the web service annotation for model transformations at various abstract levels. However, designers have to create a distinct CTT for each device to connect them with the web services in order to develop different versions of the same application on multiple devices.

Luyten and Clerckx develop an algorithm for transforming a CTT to executable state machines (Luyten and Clerckx, 2003). This is similar to the state machines used here, but does not consider multi-device environments. More recent work like (Popp et al., 2013) considers code generation for multi-device UIs, but does not consider flexible constructs like our *Any* or *All* operators.

In summary, we are not aware of any work similar to this approach. Usually, all these existing approaches handle distribution issues in more concrete models after defining the task models. In our opinion, it is however natural to consider the distribution to devices in task models directly. Instead of adding rules for executing tasks across multiple devices at the concrete model level, our introduced device labeling mechanism enables designers to define execution of tasks at the early stage.

5 CONCLUSION

In this paper, we have presented a first approach to translate multi-device task models into distributed state machines. The main novelty of this work is an algorithm for the MCTT device labeling operators *Any* and *All*, which creates distributed, coordinated state machines in a multi-device setting. To achieve this, we generate specific state machines for each involved device which include states and transitions for both tasks and necessary coordination overhead. We build upon an already existing translation algorithm, that translates ordinary CTT tasks and operators into state machines. Our approach therefore extends the translation of basic tasks and integrates the distributed characteristics of device labeling operators into the translation rules for CTTs. Overall, our paper shows that MCTTs are a valid tool to build distributed, coordinated systems with a mulitude of devices.

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