ABSTRACT

Model-based development of CPS is based on the capability of early verification of system properties on a model of the controls and the controlled physical system, and the capability of producing automatically an implementation of the model. Unfortunately, in the development of complex distributed or highly concurrent systems, the scheduling and communication delays may significantly affect the behavior of the controls. We present a framework for adding the model of schedulers, tasks and messages to Simulink models and to verify by simulation the impact of scheduling and execution times delays on the performance of the controls. Our toolset is highly modular and extensible and allows application to existing models with limited changes and even the automatic synthesis of the task and message model from an external specification.

1. INTRODUCTION

Simulink is a graphical modeling environment implementing a Synchronous-Reactive (SR) Model of Computation (MoC) for multidomain Model-Based Design (MBD) and simulation. Continuous-time, discrete-time and discrete-event systems can be defined in the model, making Simulink suitable for the design of Cyber-Physical Systems (CPSs), where the controller (discrete-time) and the plant (continuous-time) must be modeled and simulated together.

CPSs are often distributed and executed on nodes connected by a wired or wireless networks. The Simulink model of the controls is purely functional and allows the modeling and simulation of the control function executing in logical time, with the assumption that all reactions complete within the next event. However, in a real system implementation, control functionality executes in finite time, and messages are queued waiting for transmission on network(s), giving rise to latencies and jitter that may change the performance of the controls.

To represent computation and communication delays in Simulink, a possible solution is provided by the TrueTime framework from the University of Lund [7]. TrueTime integrates a Real-Time Scheduling and a network simulator in a Simulink custom block, enabling the co-simulation of the control functions considering the software (task) and message implementation details with the scheduler and resource management policies. TrueTime supports the Earliest Deadline First (EDF) and Fixed Priority (including Rate Monotonic, RM) scheduling policies [6] for single-core systems and several network standards, including Ethernet, the CAN bus and FlexRay, but also wireless networks such as 802.11b WLAN and 802.15.4 ZigBee. Presently, multi-core architectures are not supported. TrueTime is implemented as a single custom Simulink block specified as a Matlab or C++ S-Function and implements, in a monolithic fashion, the controller functionality, the task model, and the scheduler.

In this paper, we present a modular framework for the co-simulation of control functionality and controlled system dynamics with Real-Time Scheduling policies, communication mechanisms and Real-Time controllers. Similar to TrueTime, it is based on Simulink, allowing the co-simulation of any discrete-time controller model and continuous-time plant. However, our framework provides a modular and extensible architecture and allows for three key features that can be considered its main contributions.

- the addition of a task implementation model and a scheduler to an existing Simulink model with limited and localized changes. The proposed modeling structure clearly separates the controller model (functionality) from the model of the task, the scheduler, the communication mechanisms and the other attributes of the execution platform.
- the modular integration of a (possibly third-party) Real-Time Scheduling simulator and network simulator, through simple and generic interfaces. For completeness and self-consistency, we provide an adapter to an existing open source scheduling and resource management simulation project RTSim [1], and the open source network simulator framework OMNeT++ [22].
- the possibility of the automatic generation of the task, scheduler, network and message blockset from a (SysML) specification using model-to-text transformation rules to generate a Matlab script that adds the blockset to the model [16].

The tool consists of a set of Simulink custom blocks implemented as C++ S-Functions for the modeling of Schedulers, Tasks, Networks and Messages. We also implemented an abstract interface between the custom blocks and a generic simulation engine for the CPU scheduler and the network,
enabling the integration of generic simulation engines as depicted in Figure 5. The framework is freely available as open source [2]. The paper is organized as follows. In section 2, we introduce the model assumptions and provide a short summary of the Simulink semantics, its execution model and the interactions between the simulation engine and our framework. In section 3, we describe the structure of the framework, with the custom blockset and the internal structure of the adapter towards the scheduling simulator. In section 4 we provide a sample case in which different task models and scheduling policies impact the performance of the controls, as shown by the simulation results. Finally, in section 5, we provide our conclusions and a discussion of future work.

1.1 Related Work

A large variety of simulation tools are available from the industry and the academia. Most of them are geared towards the use in a specific domain. NS-3 (Network Simulator) [17] and OMNeT++ [18] are freely available discrete-event computer network simulators. They support several communication protocols and are extensible for the inclusion of new ones. In [15] a simulation environment for CAN-Ethernet networks is presented as example of extension to OMNeT++.

A very large number of projects target the evaluation of scheduling policies and the analysis of task implementations (more than 6 million hits when searching the keywords Real-Time Scheduling Simulator in Google). A necessarily incomplete list includes Yartiss [9], Storm [21], ARTISST [10], Cheddar [20], Schesim [14], Stress [5].

TrueTime [7] is a freeware Matlab/Simulink-based simulation tool that has been developed at Lund University since 1999. It provides models of multi-tasking Real-Time kernels and networks that can be used in simulation models for networked embedded control systems. TrueTime is used by many research groups worldwide to study the (simulated) impact of lateness and deadline misses on controls.

Several research works investigate the consequences of computation (scheduling) and communication delays on controls. An overview on the subject can be found in [4], a discussion of on-line (scheduled) sampling can be found in [8]. Also, an analysis of control activation models based on events rather than periodic triggers (and the possible improvements with respect to the CPU resource) are discussed in [3] and [13].

The TrueTime Kernel block simulates a computer node with a generic Real-Time kernel, A/D and D/A converters, external interrupt inputs and network interfaces. The block is configured via an initialization script (usually written in Matlab code), where a specific API is used by the designer to create tasks, timers and interrupt handlers and define the scheduling policy and the communication resources.

In TrueTime, the model of task code is represented by code functions that are written in either Matlab or C++ code. A TrueTime developer has two options: hand-code the control logic and lose availability of Simulink (control) toolboxes, or call external discrete-time Simulink models from within the code functions using a mechanism based on the MATLAB built-in operator sim() with several limitations: signal-generator blocks that use the simulation time and blocks for which it is not possible to specify the sample rate (e.g., the Discrete Derivative block) cannot be used. In addition, data connections among Simulink models need to be implemented in code using a purposely offered API and the application of a TrueTime Scheduler to an already existing Simulink model of controls requires substantially rewriting, mixing the controller functionality, the model of the task set, the scheduler, and the physical execution platform. Because of the monolithic architecture and the number of code artifacts that are needed for system configuration (e.g., initialization script and code functions), the current TrueTime implementation is hardly compatible with an automatic model generation and a Model-to-Model (M2M) transformation flow.

SimEvents [19] is a commercial toolbox developed by The MathWorks, providing a discrete-event simulation engine and component library for Simulink. It enables event-driven communication modeling between Simulink components to analyze and optimize end-to-end latencies, throughput, packet loss, and other performance characteristics. The component library allows the designer to customize processing delays, prioritization, and other operations to represent systems that range from manufacturing processes, to hardware architectures and sensor/communication networks. Because of its generality, SimEvents has no explicit notion of task, Real-Time scheduler, network protocol or hardware component. They need to be built as libraries using the queue and server blocks.

2. BASIC CONCEPTS AND ASSUMPTIONS

Simulink implements a Synchronous- Reactive (SR) model of computation integrating continuous-, discrete-time and discrete events (triggered) subsystems and blocks. Continuous-type blocks process continuous-time signals and produce as output other continuous signal functions according to the block description, typically a set of differential equations. The equations that compute the dynamics of the continuous part are integrated by a solver at fixed or variable time steps. A variable step solver is invoked at those points in time that are relevant for the dynamics of the system they compute (major steps and zero-crossing points).

Discrete-Time Simulink blocks are activated at periodic-time instants and process input signals, sampled at periodic instants, producing a set of periodic-output signals and the state updates. Finally, triggered blocks are only executed on the occurrence of a given event (a signal transition or a function call).

A fundamental part of the model executable semantics are the rules dictating the evaluation order of the blocks. Any block for which the output is directly dependent on its input (i.e., any block with direct feedthrough) cannot execute and produce outputs until the blocks driving its inputs execute. The set of topological dependencies implied by direct feedthrough blocks defines a partial order. When the simulation starts, blocks are ordered and a total order of execution compatible with the partial order of execution is determined. When a block is triggered (activated), inputs are sampled and output update and state update functions computed in sequence to produce the system outputs.

The Simulink engine computes the states and outputs of the system at time points (steps) from the simulation start time to the finish time. The length of time between steps is called step size. Variable step solvers divide the simulation timespan in major and minor time steps. The solver produces a result at each major time step. Any point in time that is relevant for the dynamic of the controlled or the con-

1http://www3.control.lth.se/truetime/LICENSE.txt
controller system corresponds to a major step. For example, all the triggering instants of discrete-time (controller) subsystems correspond to major steps. A minor time step is a subdivision of the major time step used to improve the accuracy in the computation of the system dynamics and find the point in time when continuous-time system have a zero-crossing point, that is a point when some of the state variables cross a zero threshold (a significant change of state).

Simulink System Functions (S-Functions) are a mechanism for extending the set of predefined Simulink blocks. An S-function is a description of a Simulink block written in Matlab, C, C++ or Fortran. Interactions between the Simulink simulation engine and custom blocks occurs through a predefined set of API functions.

Figure 1 shows the simulation cycle at runtime with the major and minor steps and the points in the cycle in which the simulation engine invokes the API functions specified for the S-function blocks. Among those, themdlOutputs is used to update the outputs of the custom block, themdlUpdate to update the internal state of the custom block andmdlZeroCrossing to define the signals that determine the zero-crossing points and possibly force them (set a time instant for a future major step). The same task can be achieved by using themdlGetTimeOfNextVarHit that allows to define a future time instant for a major step.

![Simulation cycle in Simulink](image)

**Real-Time Scheduling Simulator.**

A Real-Time Scheduling Simulator is a Discrete Event System (DES) implementing an event handling mechanism (typically with a queue). It reacts to tasks arrival events and dispatches the currently active tasks from the ready queue according to a fixed or dynamic priority-based scheduling algorithm. Tasks arrival events can arrive asynchronously or periodically and are ordered in the event queue in ascending order following (i) the event occurrence time (ii) a causality order for those with equal occurrence time. To preserve causality, a task is dispatched only when all the events at the current time have been processed. At any point in time, the next scheduling event can be the termination of the task currently in execution, or the arrival event of a task, that can possibly cause a preemption (if the new task has higher priority) and a context switch.

In an RT simulator, tasks execute according to a model of (time-consuming) computation. Our framework assumes the same model as in TrueTime (which is also suited to the typical code generation process for Simulink models). The execution of a task is split in preemptable units called segments, informally corresponding to the execution of a function called by the task main code. Each segment is identified by an execution time (possibly randomly generated according to a given distribution) and all segments in a task are executed in a sequence.

When the RT simulator is integrated with Simulink, segments map one-to-one to subsystems and the execution order of the segments in a task must match the order of execution imposed by the model semantics. The time duration of each task segment, corresponds to the execution time of the corresponding code function implementing the sub-system (and possibly generated from it in an automatic code generation flow). Formally, the execution model is the following (a strict subset of the Simulink semantics).

- $V = \{S_1, \ldots, S_{|V|}\}$, the set of functional sub-systems in the Simulink model. A functional controller subsystem $S_i$ is characterized by a worst case execution time $\gamma_i$ for its generated execution code on a given platform. We assume a subsystem reads or samples all its inputs when it starts executing, and generates the outputs when it completes execution. A subsystem $S_i$ may have input and output ports. We assume the designer partitions the controller (discrete-time) model into single rate subsystems and that all input ports carry signals with a uniform sampling period $t_i$. The result of the block computation is a set of signals with the same rate, produced on the output port. The sampling period $t_i$ of the input signal is also the activation period of the block.
- $E = \{e_1, \ldots, e_{|E|}\}$ is the set of links. A link $e_i = (S_h, S_k)$ connects an output port of subsystem $S_h$ (source) to an input port of $S_k$ (sink).
- A precedence relation may exist between a pair of subsystems $S_i$ and $S_j$. The notation used is $S_i \prec S_j$.

On the side of the task model, supported by the RT simulator, we have

- $T = \{\tau_1, \ldots, \tau_{|T|}\}$ is the set of tasks. Each task $\tau_i$ has an activation period $T_i$ or activation event $e_i$ and an optional priority $\pi_i$ (or other scheduling attributes). Periodic tasks have zero offset, thus they start at the same time instant $t = 0$.
- A mapping relation $mt(S_i, \tau_j, k)$ is defined between a controller subsystem $S_i$ and a task $\tau_j$ meaning that the code implementing $S_i$ is executed in the context of task $\tau_j$ with order index $k$. A mapping relation is only possible if the execution rate of $S_i$ and $\tau_j$ are the same (the constraint could be relaxed allowing for integer divisors). If two subsystems are mapped onto the same task, the mapping order index must match their partial order of execution. If they are on different tasks, the execution order must be guaranteed by the priorities assigned to the tasks.
- Tasks are scheduled for execution on a single- or multi-core platform according to a defined scheduling policy.

The major steps of the Simulink simulation must include all the periodic activation times of tasks as well as the aperiodic events that lead to the activation of other tasks. Every time a major step occurs, the block implementing the...
Real-Time Scheduling Simulator is invoked and processes (if there is any) the task arrival event and any other event that is active at the same time. The task activation instant corresponds to the activation of the first task segment. Next, the Real-Time scheduler determines the tasks to be set in execution and the execution time for their current segments, determining the points in time when the current segments are expected to complete. These times are set as future major step times in the Simulink simulation using the zero crossing or next var hit API calls.

The actual start and completion times of the task segments must correspond to the times when the corresponding subsystems read or sample their inputs and produce their outputs. To guarantee this execution semantics, the activation of each subsystem must be changed from periodic to function activated (Figure 2), and a latch barrier must be added on all its outputs. The signals activating the subsystem (and its input sampling) and the output latch are generated by the task blocks upon the beginning of the execution and the completion of the corresponding task segment. Zero-execution time assumption is replaced by the finite-execution time assumption, enabling the simulation of the scheduling mechanisms upon the Simulink model.

Figure 2: The execution of subsystems modeled through segments.

Figure 2 shows the activation mechanism of a block (D in the example). When a task segment starts executing, the corresponding block is activated. However, the output value is not instantaneously available for the other blocks in the system. The segment execution can be interrupted and its execution time can take longer than the original segment length since the task can be preempted to execute high-priority tasks. To handle this, the output signal is latched and enabled as output only when the segment terminates its execution. The segment completion results in the signal update at the output of the latch.

**Network Simulator.**

Like a Real-Time Scheduling Simulator, a Network Simulator is a DES simulating nodes exchanging messages over a network infrastructure with a given communication protocol. The simulator defines the timed events related to the transmission and arrival of messages by the networked nodes. The communication protocol is the core attribute of the communication network. It defines the set of rules according to which messages are selected for transmission on shared physical links and ultimately determines the latency of messages together with the attributes that define the network speed and reliability. It is therefore important that a Network Simulator supports a large set of protocols and can be easily extended to include new protocols.

Formally, a network can be described with:

- \( M = \{m_1, \cdots, m_{|M|}\} \), a set of messages.
- \( N = \{n_1, \cdots, n_{|N|}\} \), a set of networks.

- A mapping relation \( mm(m_i, n_j) \) is defined between messages and networks, meaning that message \( m_i \) is transmitted over the network \( n_j \).
- A mapping relation \( ml(l_i, m_j) \) is defined between links and messages, meaning that the data of the signal exchanged over \( l_i \) is mapped onto message \( m_j \). Each link \( l_i \) can be mapped onto at most one message. Many-to-one mappings are allowed (signal multiplexing). If \( l_i \) is not mapped to any message, then its implementation consists of local communication (typically a shared variable).

The synchronization between the Network Simulator and Simulink, is orchestrated by our Simulink Network custom block. The major steps of the Simulink simulation must include all the periodic activation times of messages, as well as the aperiodic events that lead to aperiodic transmissions of messages. At every major step, the Network block is invoked and processes the possible message transmission and arrival events and determines when the currently sent messages are expected to be received. These time instants are set as future major steps in the Simulink simulation.

When a signal is sent by a message over a network, the signal is sampled and the message is assembled and put into a ready queue of messages ready to be sent. When it reaches the receiver, the message is disassembled and its signal values are available to be read. The time required to deliver the message depend on the underlying protocol and the network traffic. To guarantee this execution semantics, each networked link is replaced with a double latch barrier as highlighted in bottom of Figure 3. The Zero-communication delay assumption is replaced by the finite-communication delay enabling the simulation of the network exchange mechanism over the network.

![Figure 3: The transmission of information signals packed into messages under the control of the network block.](image)

When a message is sent, the send barrier is activated and the corresponding link sampled. The signal is not instantaneously propagated to the receiver block but gated by a second latch that blocks the signal until the message is actually delivered to the receiver node. When the message is delivered, the arrival barrier is activated, and the signal is made available to the other blocks in the system.

3. **ARCHITECTURE**

3.1 **Execution Model**

Our framework adds the capability of simulating Real-Time task execution of Simulink models on single- and multi-
random computation times include the uniform distribution between a minimum and a maximum value, the exponential and the Dirac delta distributions (an example is shown in the following code section).

task_code = {'fixed(7)'; 'delay(unif(3,8))'};

The block Kernel has two input ports: duration and trigger. On the duration port it receives an array of values, one for each Task block, with the indication of the duration of the next segment to be executed. On the second port, it receives the array of activation signals of aperiodic tasks (from external sources). The block has one output port, named activ, which is used to signal to each task the execution of the current segment. The block Kernel uses a zero-crossing function to require future activations (from the Simulink engine) in correspondence of scheduled events, but it is also activated synchronously with the arrival of aperiodic tasks.

The block Kernel is responsible for keeping the scheduling simulation aligned with the system simulation. At each activation, it checks for any aperiodic requests. If there is any, it activates the corresponding aperiodic tasks in the Real-Time Scheduling Simulator. Next, it advances the Real-Time Scheduling Simulator by looking for the next event in the simulator’s event queue. Two types of events are relevant for the simulation: the segment completion and task completion. In case an event of the first type occurs, Kernel reads the input signal on the port duration at the index corresponding to the task that completed the segment, and dynamically creates a new instruction and insert it in the corresponding task. Finally, once it detects which task has generated the event, it sends an activation signal to the activ port to trigger the corresponding Task. If the event task completion is detected, Kernel simply reset the internal state of the corresponding task clearing the past history of the executed segments.

A number of parameters configure the (simulated) kernel and are set through the Kernel mask dialog. Three scheduling policies, namely Deadline Monotonic (DM), Fixed-Priority (FP) and Earliest Deadline First (EDF), are readily selectable from a context menu. Optionally, the designer can provide the type and the configuration parameters (if any) of other scheduling policies, provided that they are supported by the underlying Real-Time Scheduling engine. The designer can specify the number of cores on which the task execution is simulated. The current implementation of Kernel with RTSim, supports multi-core architectures with global scheduling policies. The mask dialog has one edit field for specifying the name of the Matlab variable (cell array) that describes the type and the timing properties of the (heterogeneous) task set (an example in the following code section).

task_set = {'PeriodicTask', 0.004, 0.004, 0;
            'PeriodicTask', 0.006, 0.006, 0};

Tasks can be periodic or aperiodic and timing properties include interarrival time, relative deadline and initial offset. Optionally, task priorities (for tasks scheduled according to FP) and core affinities can be specified for each task. Finally, in case several external RT simulators are supported, a context menu enables the designer to select the one that is used to perform the simulation.
3.1.2 Network

Figure 3 (top) shows the structure of the Network and Message blocks. The Message blocks are driven by the Network block using its state port. The Network block communicates to each Message block the state of the simulated message (send or receive) over the network. The block Message uses the function call output port activ to trigger the barriers shown in Figure 3 (bottom) according to the message state received from the Network block.

When a message must be sent over the network, the Network block sends the send state to the appropriate Message block. Then, the Message block triggers the send barrier as shown in Figure 3. Once the message is delivered, the Network block will change the state signal (of the delivered message) to receive and the Message block will trigger the arrival barrier as shown in Figure 3.

3.2 The RT Simulator API Layer

The blocks Kernel and Network rely on external engines to perform the processor scheduling and network simulation. Their implementations are not tied to a specific tool or framework, and are designed according to the basic principles of object-oriented programming to provide an easy integration with external scheduling and network simulators.

The design of the Real-Time Simulation API layer is based on the observation that every RT simulation framework basically consists of two high level components: an event handling system and, on top of it, the actual scheduling simulator. The first one defines a set of objects that provide a representation of events and event queues, and provides an API that enables the creation and deletion of events and their insertion in and extraction from the event queue. The second one uses the definitions of event (typically after specialization) and event queue and realizes the actual Real-Time Scheduling Simulation functionality. It implements the concepts of task (e.g., periodic, aperiodic), scheduling policy (e.g., DM, FP, EDF), and kernel (e.g., single- or multi-core, with a scheduler and a resource manager). The RT Simulator API layer abstracts these concepts and enables the development of the Kernel S-Function so that it depends upon a set of interfaces classes, rather than upon their concrete implementations (i.e., a specific RT simulation framework).

The RT Simulator API layer defines three virtual classes that are used by the Kernel S-Function, namely Kernel, SimTask and Event. These define a narrow interface for the kernel, task and event data structures offered by the external RT simulator. The object adapter pattern [12] is used to bind the abstract interfaces, used by the S-Function (client), with the third-party software represented by the RT simulator. Each class defines a set of operations as pure virtual functions.

The following is the set of virtual methods to be specialized by the refinement of the Kernel class realizing the adaptation to the Real-Time Scheduling Simulator. Another set of virtual methods is defined for the adapter classes for tasks and events (not shown because of space constraints).

```cpp
/* Real-Time Scheduling Simulator API */
virtual void initializeSimulation(const double, const double* const*) = 0;
virtual void processNextEvent() = 0;
virtual int getTimeOfNextEvent() = 0;
virtual int getNextWakeUpTime() = 0;
virtual int getRunningTasks() = 0;
```

Their implementation is demanded to the object adapter, which calls adaptee operations to actually carry out the requests. Figure 5 shows the interaction of the custom Kernel block with the simulation engine.

A Network Simulator framework is also based upon an event handling mechanism (discrete event simulator) with, on top of it, a message handling mechanism. The Network API layer defines three virtual classes that are used by the Network S-Function: Network, SimMessage and Event. The object adapter pattern is still used to bind the abstract interface with the third-party Network simulator.

```cpp
// Network simulator API */
virtual void processNextEvent() = 0;
virtual int getTimeOfNextEvent() = 0;
virtual int getNextWakeUpTime() = 0;
```

Similar to the processor scheduler, our framework includes the adapter towards one existing network simulator. In this case, we realized and tested the connection towards the very popular OMNet++ package, thereby showing the proposed extensibility and adaptation. A CAN protocol implemented on top of OMNet++ [15] has been used as the first example of an embedded communication protocol.

In order to create an instance of a class without making the S-Function (both Kernel and Network) depend upon the concrete class, the factory method pattern [12] is used. Each adapter defines a method called createInstance(), which takes a std::vector of std::string objects as input argument. The std::string objects describe a specific configuration for the adapter to be instantiated and are provided by the user through the S-Function mask. For example, a specific configuration for a Kernel may define the scheduling policy, the task set, the number of cores, etc. Adding adapters for new external Real-Time Scheduling Simulators is easy and just requires to register the factory method of the new adapter class to a generic factory class. It does not require any modification to the code of the factory.

4. EXAMPLE

A case study showing a possible implementation of three servo PID controls, adapted from the TrueTime example library is used to illustrate the capability and the output of the framework. The example consists of three DC servos with their continuous-time dynamics (the plant) modeled by a continuous time system and controlled by three
signals from the controls and forwards them to the motors. and sent to the PID using a periodic CAN message implementation assumptions are the same as in the TrueTime example. The behavior and the execution time of systems. Each subsystem is executed in a segment with an execution time of 2 ms. The three controller subsystems (discrete-time) PID controllers with the same coefficients (same functional behavior). The three controller subsystems are mapped for execution on three tasks (T₀, T₁, T₂ each running one segment) running on a single processor. The task periods are T₀ = 4, T₁ = 5 and T₂ = 6 milliseconds respectively. The example is shown in Figure 6 with the appropriate Kernel and Task blocks. Tasks specification are supplied as workspace variables. The PID controllers (contrary to the TrueTime example) are implemented as Simulink subsystems. Each subsystem is executed in a segment with an execution time of 2 ms, giving a total CPU load higher than 100% (an overload condition). The behavior and the implementation assumptions are the same as in the TrueTime example.

In addition, the position of the motors is read by sensors and sent to the PID using a periodic CAN message m₂. Another periodic CAN message m₁ collects all the command signals from the controls and forwards them to the motors. The period of the two messages is 4 ms. m₂ (the message with the sensor data) has higher priority. The CAN message blocks are shown at the top of Figure 6, right below the task blocks and their simulated transmission is controlled by the Network block (same line, on the left of the figure).

We simulated the example on several runs, with and without networking (and the associated sampling and transmission delays) and using different scheduling policies, such as Rate Monotonic (RM, static priority assignment) and Earliest Deadline First (EDF, dynamic priority) policies. The results are shown in Figure 7. The top three graphs show the output of the motors for the three PID controllers when the corresponding task implementations are scheduled using RM. Task priorities are assigned in order to the three tasks,
\[ \tau_0 = 1, \tau_1 = 2, \tau_2 = 3. \] The reference signal for the motors is a square wave. As a reference, the output of the controls when the computation and communication delays are not considered (zero logical time execution: a normal Simulink run executing without our framework blocks) is shown as a thick light line. The output of the model with the computation delays only (no networking) is a thick black line and the output when also the message delays are considered is shown as a dashed line.

The top graph in the figure shows how the lowest priority task (\(\tau_2\)) is losing too many deadlines and the control is not stable when considering the scheduling delays alone (of course, the same is true when communication delays are considered). The use of an EDF scheduling policy with the abortion of tasks trespassing the deadline results in a completely different set of results, as shown on the bottom three graphs of Figure 7. None of the outputs is unstable and, despite some performance degradation (this time the scheduling delay tends to be spread among the three tasks) the motion of the motors is controlled.

5. CONCLUSIONS AND FUTURE WORK

The framework for Real-Time Scheduling Simulation in Simulink is part of a larger project aimed at system-level modeling, timing analysis and automatic generation of an implementation for Real-Time distributed systems [11]. The overall project consists of a merger of MBD and MDE methodologies. The functional model of the physical controlled system and the controller functions is created in Simulink and validated by simulation. Next, a functional abstraction is imported in Papyrus (SysML). The distributed execution architecture, including CPUs, networks, devices, operating systems, resource managers and protocol stacks, is then modeled in SysML and the functional model is mapped onto the execution architecture creating a model of the software (including task) and message implementation. After mapping, the worst case execution times of functions (implementing subsystems) and tasks are estimated, and the implementation model is then validated against timing constraints and by verifying that the latencies and jitter added by the scheduling and communication delays do not exceedingly deteriorate the performance of the controls.

6. REFERENCES