TrueTime 2.0 – Reference Manual

Anton Cervin
Dan Henriksson
Martin Ohlin

Department of Automatic Control
Lund University
Feburary 2016

Contents

1. Introduction

This manual describes the use of the Matlab/Simulink-based [The Mathworks, 2001] simulator TrueTime, which facilitates co-simulation of controller task execution in real-time kernels, network transmissions, and continuous plant dynamics. The simulator is presented in [Henriksson *et al.*, 2003; Cervin *et al.*, 2003; Henriksson *et al.*, 2002; Andersson *et al.*, 2005], but be aware that several differences from these papers exist.

The manual describes the fundamental steps in the creation of a TrueTime simulation. This include how to write the code that is executed during simulation, how to configure the kernel and network blocks, and what compilation that must be performed to get an executable simulation. The code functions for the tasks and the initialization commands may be written either as C++ functions or as Matlab M-files, and both cases are described.

Several tutorial examples are provided, treating standard and networked PID-control, scheduling, overrun handling, synchronization, control over wireless networks, mote coordination, wireless ad-hoc routing using AODV, mobile robot soccer, and more.

The manual also describes some of the internal workings of TrueTime, including the task model, implementation details, and timing details. The network blocks and the radio model used for the wireless simulations are also presented in some detail. A TrueTime command reference with detailed explanations of all functionality provided by the simulator is given at the end of the manual.

For questions and bug reports, please direct these issues to

`truetime@control.lth.se`

2. Getting Started

Download the zip archive from the TrueTime homepage. Then

1. Unpack all files to some suitable directory $DIR
2. Start Matlab R2012a or later and cd to $DIR
3. Run `init_truetime.m` to add the necessary Matlab paths and to set the TTKERNEL environment variable.

Issuing the command

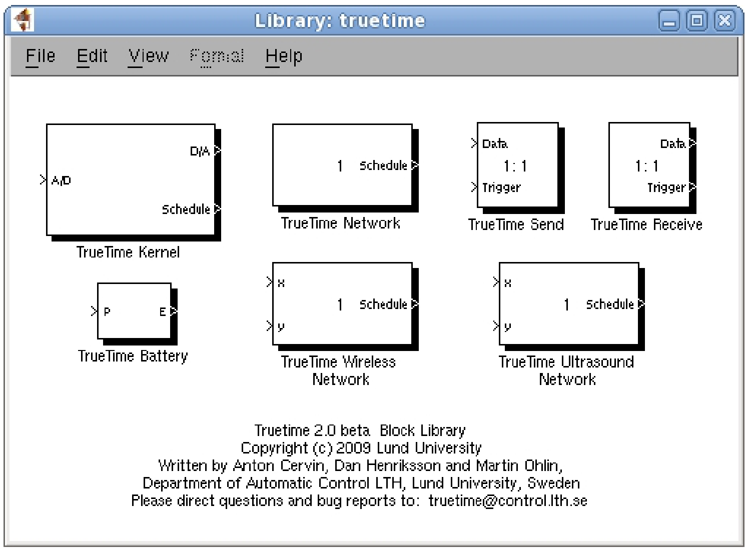
```
>> truetime
```

from the Matlab prompt will now open the TrueTime block library, see Figure 1.

2.1 Compilation

Since the TrueTime archive contains pre-compiled files, no compilation should be required to run TrueTime with the M-file API.

However, TrueTime also supports simulations written in C++ code, which then must be compiled. In this case, you first need to configure your C++ compiler in Matlab. This can be done by issuing the command



Truetime 2.0 beta Block Library
Copyright (c) 2009 Lund University
Written by Anton Cervin, Dan Henriksson and Martin Ohlin,
Department of Automatic Control LTH, Lund University, Sweden
Please direct questions and bug reports to: truetime@control.lth.se

Figure 1 The TRUETIME 2.0 block library.

```
>> mex -setup C++
```

In the setup, make sure that you change from the Matlab default compiler to a proper C++ compiler. For more detailed instructions on how to compile individual simulations, see Section 6 in this manual.

3. Using the Simulator

The TRUETIME blocks are connected with ordinary Simulink blocks to form a real-time control system, see Figure 2. Before a simulation can be run, however, it is necessary to initialize kernel blocks and network blocks, and to create tasks, interrupt handlers, timers, events, monitors, etc for the simulation.

As mentioned above, the initialization code and the code that is executed during simulation may be written either as Matlab M-files or as C++ code (for increased simulation speed). How the code functions are defined and what must be provided during initialization will be described below. It will also be described how the code is compiled to executable Matlab code.

4. Writing Code Functions

The execution of tasks and interrupt handlers is defined by code functions. A code function is further divided into code segments according to the execution model shown in Figure 3. All execution of user code is done in the beginning of each code segment. The execution time of each segment should be returned by the code function.

4.1 Writing a Matlab Code Function

The syntax of a Matlab code function implementing a simple P-controller is given by Listing 1.

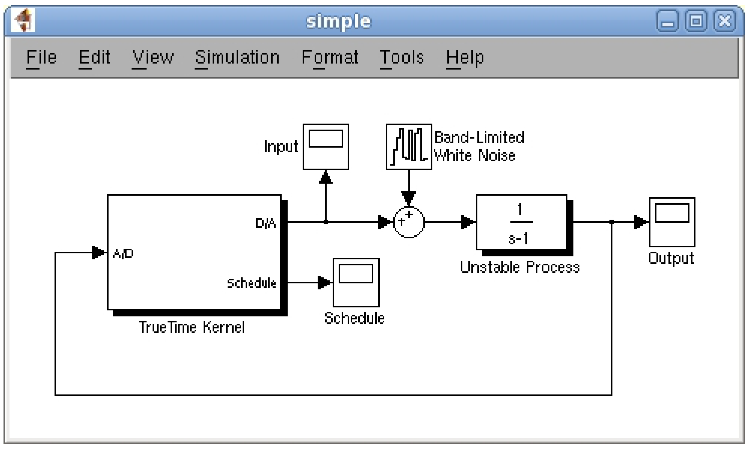


Figure 2 A TRUETIME Kernel block connected to a continuous plant.

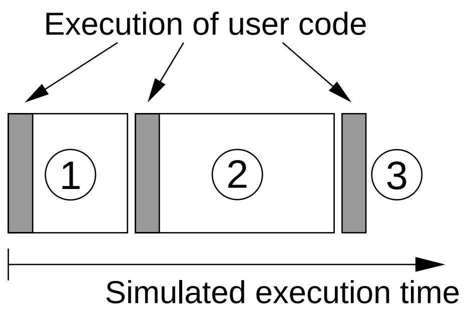


Figure 3 The execution of user code is modeled by a sequence of segments executed in order by the kernel.

The variable `segment` determines which segment that should be executed, and `data` is a user-defined data structure that has been associated with the task when it was created (see `ttCreateTask` and `ttCreatePeriodicTask` in the command reference). The data is updated and returned by the code function. The code function also returns the execution time of the executed segment.

In this example, the execution time of the first segment is 2 ms. This means that the delay from input to output for this task will be at least 2 ms. However, preemption from higher priority tasks may cause the delay to be longer. The second segment returns a negative execution time. This is used to indicate end of execution, i.e. that there are no more segments to execute.

`ttAnalogIn` and `ttAnalogOut` are real-time primitives used to read and write signals to the environment. Detailed descriptions of these functions can be found in the command reference at the end of this manual.

4.2 Writing a C++ Code Function

Writing a code function in C++ follows a similar pattern as the code function described in Listing 1. The corresponding C++ syntax for the P-controller code function is given in Listing **??**. We here assume the existence of a data structure `Task_Data` that contains the control signal u and the controller gain, K.

4.3 Calling Simulink Block Diagrams

In both the C++ and m-file cases, it is possible to call Simulink block diagrams from within the code functions. This is a convenient way to implement controllers. Listing 2 shows an example where the discrete PI-controller in Figure 4 is used in a code function. See the command reference at the end of this manual for further explanation of the command `ttCallBlockSystem`.

Listing 1 Example of a P-controller code function written in Matlab code.

```
function [exectime,data] = ctrl_code(segment, data)

switch segment
  case 1
    y = ttAnalogIn(1);
    data.u = -data.K * y;
    exectime = data.exectime;
  case 2
    ttAnalogOut(1, data.u)
    exectime = -1;
end
```

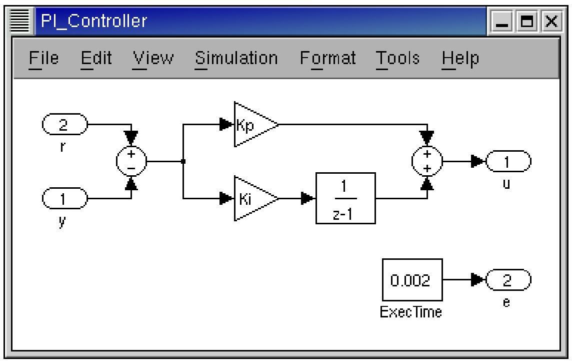


Figure 4 Controllers represented using ordinary discrete Simulink blocks may be called from within the code functions. The only requirement is that the blocks are discrete with the sample time set to one.

Listing 2 Simulink block diagrams are called from within code function using the TRUE-TIME function `ttCallBlockSystem`.

```
function [exectime, data] = PIcode(segment, data)

switch segment,
  case 1,
    inp(1) = ttAnalogIn(1);
    inp(2) = ttAnalogIn(2);
    outp = ttCallBlockSystem(2, inp, 'PI_Controller');
    data.u = outp(1);
    exectime = outp(2);
  case 2,
    ttAnalogOut(1, data.u);
    exectime = -1; % finished
end
```

5. Initialization

Initialization of a TrueTime kernel block involves specifying the number of inputs and outputs of the block, defining the scheduling policy, and creating tasks, interrupt handlers, events, monitors, etc for the simulation. This is done in an initialization script for each kernel block. The initialization script can (in the Matlab case) also take an optional parameter to limit the number of similar code functions. The other TrueTime kernel block parameters are described in Section 7.

In the examples given below, the initialization script is called `example_init`, both in the Matlab and C++ cases. The optional parameter is called `argument` when it is used.

5.1 Writing a Matlab Initialization Script

The initialization code in Listing 3 shows the minimum of initialization needed for a TrueTime simulation. The kernel is initialized by providing the number of inputs and outputs and the scheduling policy using the function `ttInitKernel`. A periodic task is created by the function `ttCreatePeriodicTask`. The period of the task is given by the init argument of the TrueTime Kernel block dialogue. (Note that the init argument may be an arbitrary Matlab struct.) This task uses the code function `Pcontroller` that was defined in Listing 1. See the command reference for further explanation of the functions.

In the Matlab case, you may experience that nothing changes in the simulations, although changes are being made to the code functions or the initialization script. If that is the case, type the following at the Matlab prompt

```
>> clear functions
```

To force Matlab to reload all functions at the start of each simulation, issue the command (assuming that the model is named `mymodel`)

```
>> set_param('mymodel', 'InitFcn', 'clear functions')
```

Listing 3 Example of a TrueTime initialization script in the Matlab version. The kernel is initialized using the function `ttInitKernel`, and a periodic task is created that uses the P-controller code function from Listing 1. The period of the controller is passed to the initialization script as a parameter.

```
function simple_init

ttInitKernel('prioFP')

data.K = 2;            % controller proportional gain
data.exectime = 0.1;   % control task execution time
starttime = 0.0;       % control task start time
period = 0.5;          % control task period

ttCreatePeriodicTask('ctrl_task', starttime, period, 'ctrl_code', data)
```

Listing 4 Template for writing initialization scripts in C++. The final script is actually a complete Simulink S-function, since the included file, `ttkernel.cpp`, contains the Simulink callback functions that implement the kernel.

```
#define S_FUNCTION_NAME filename
#include "ttkernel.cpp"

// insert your code functions here

void init() {
// perform the initialization
}

void cleanup() {
// free dynamic memory allocated in this script
}
```

5.2 Writing a C++ Initialization Script

An initialization script in C++ must follow a certain format given by the template in Listing 4. The included file `ttkernel.cpp` contains the Simulink callback functions that implement the TrueTime kernel, meaning that the initialization script is actually a complete Matlab S-function. `filename` should be the name of the source file, e.g. if the source file is called `example_init.cpp`, `S_FUNCTION_NAME` should be defined to `example_init`.

The `init()`-function is called at the start of simulation (from the Simulink callback function `mdlInitializeSizes`), and it is here all initialization should be performed. The initial argument supplied in the TrueTime Kernel block dialogue can be retrieved using the function `ttGetInitArg`. Any dynamic memory allocated from the `init()`-function can be deallocated from the `cleanup()`-function, which is called at the end of simulation. A pointer to aritrary user data can be stored using `ttSetUserData` and later retrieved using `ttGetUserData`.

The C++ version of the Matlab initialization script of Listing 3 is given in Listing 5.

6. Compilation

Compilation requires that a proper C++ compiler has been configured in Matlab as described in Section 2.1. If needed, the TrueTime kernel may be re-compiled by issuing the command

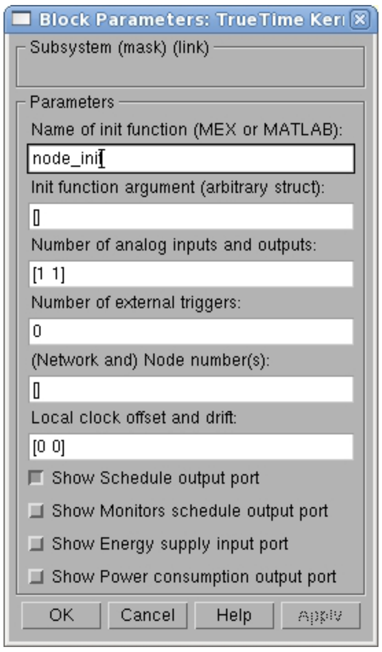
```
>> make_truetime
```

from the Matlab prompt. This script compiles the kernel and network S-functions and the MEX-files for the TrueTime primitives.

In the C++ case, the initialization script (`example_init.cpp` in the example from the previous section) must be compiled to produce a Matlab MEX-file for the simulation. This is done by the command

Listing 5 Example of a TRUETIME initialization script in the C++ version. Corresponds to the Matlab version from Listing 3.

```
#define S_FUNCTION_NAME simple_init
#include "ttkernel.cpp"

// Data structure used for the task data
class CtrlData {
public:
  double u;
  double K;
  double exectime;
};

// Code function for the P-controller
double ctrl_code(int segment, void* data) {

  CtrlData *d = (CtrlData*)data;
  double y;

  switch (segment) {
  case 1:
    y = ttAnalogIn(1);
    d->u = - d->K * y;
    return d->exectime;
  case 2:
    ttAnalogOut(1, d->u);
    return FINISHED;
  }
}

// Kernel init function
void init() {

  // Allocate memory for the task
  CtrlData *data = new CtrlData;

  // Store a pointer to the task data so that it can be cleaned up
  ttSetUserData(data);

  data->K = 2.0;
  data->exectime = 0.1;

  ttInitKernel(prioFP);
  ttCreatePeriodicTask("ctrl_task", 0.0, 0.5, ctrl_code, data);
}

// Kernel cleanup function
void cleanup() {

  delete (CtrlData *)ttGetUserData();
}
```



Name of init function (MEX or MATLAB): node_init

Init function argument (arbitrary struct): []

Number of analog inputs and outputs: [1 1]

Number of external triggers: 0

(Network and) Node number(s): []

Local clock offset and drift: [0 0]

☑ Show Schedule output port

☐ Show Monitors schedule output port

☐ Show Energy supply input port

☐ Show Power consumption output port

Figure 5 The dialog of the TrueTime kernel block.

```
>> ttmex example_init.cpp
```

The initialization file needs to be recompiled each time changes are made to the code functions or to the initialization functions.

Note: The `ttmex` command is the same as the ordinary `mex` command but includes the path to the kernel files (`ttkernel.cpp`) automatically.

7. The TrueTime Kernel

The kernel block is configured through the block mask dialog, see Figure 5, with the following parameters (some parameters can also be set at run-time with the command `ttSetKernelParameter`):

Init function The name of the initialization script, see Section 5.

Init function argument an optional argument to the initialization script. This can be any Matlab struct.

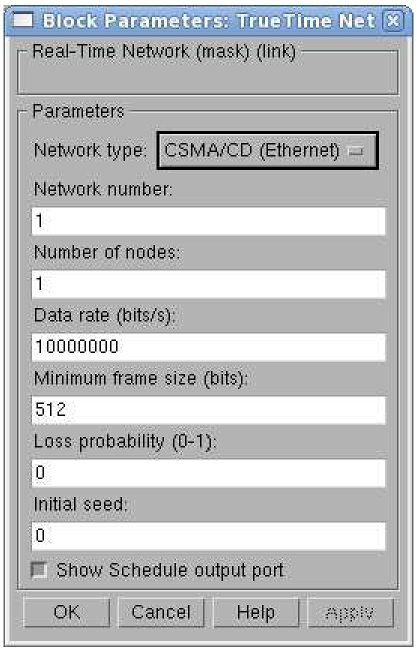
Battery Enable this check box if the kernel should depend on a power source.

Clock drift The time drift, 0.01 if the local time should run 1% faster than the nominal time (the actual simulation time).

Clock offset A constant time offset from the nominal time.

7.1 Dynamic Voltage Scaling

With the use of `ttSetKernelParameter`, the current execution speed of the kernel can be set and also the current power consumption. This makes it possible to simulate Dynamic Voltage Scaling. This functionality can be useful together with the battery block, see Section 11.


Block Parameters: TrueTime Net

Real-Time Network (mask) (link)

Parameters

Network type: CSMA/CD (Ethernet)

Network number:
1

Number of nodes:
1

Data rate (bits/s):
10000000

Minimum frame size (bits):
512

Loss probability (0-1):
0

Initial seed:
0

Show Schedule output port

Figure 6 The dialog of the TrueTime network block.

8. The TrueTime Network

The TrueTime network block simulates medium access and packet transmission in a local area network. When a node tries to transmit a message (using the primitive `ttSendMsg`), a triggering signal is sent to the network block on the corresponding input channel. When the simulated transmission of the message is finished, the network block sends a new triggering signal on the output channel corresponding to the receiving node. The transmitted message is put in a buffer at the receiving computer node. A message contains information about the sending and the receiving computer node, arbitrary user data (typically measurement signals or control signals), the length of the message, and optional real-time attributes such as a priority or a deadline.

Six simple models of networks are supported: CSMA/CD (e.g. Ethernet), CSMA/AMP (e.g. CAN), Round Robin (e.g. Token Bus), FDMA, TDMA (e.g. TTP), and Switched Ethernet. The propagation delay is ignored, since it is typically very small in a local area network. Only packet-level simulation is supported—it is assumed that higher protocol levels in the kernel nodes have divided long messages into packets, etc.

The network block is configured through the block mask dialog, see Figure 6. Using the command `ttSetNetworkParameter`, see Section 14, it is also possible to change some parameters on a per node basis. The following network parameters are common to all models:

Network number The number of the network block. The networks must be numbered from 1 and upwards. Wired and wireless networks are not allowed to use the same number.

Number of nodes The number of nodes that are connected to the network. This number will determine the size of the `Snd`, `Rcv` and `Schedule` input and outputs of the block.

Data rate (bits/s) The speed of the network.

Minimum frame size (bits) A message or frame shorter than this will be padded to give the minimum length. Denotes the minimum frame size, including any overhead introduced by the protocol. E.g., the minimum Ethernet frame size, including a 14-byte header and a 4-byte CRC, is 512 bits.

Loss probability (0–1) The probability that a network message is lost during transmission. Lost messages will consume network bandwidth, but will never arrive at the destination.

8.1 CSMA/CD (Ethernet)

CSMA/CD stands for Carrier Sense Multiple Access with Collision Detection. If the network is busy, the sender will wait until it occurs to be free. A collision will occur if a message is transmitted within 1 microsecond of another (this corresponds to the propagation delay in a 200 m cable; the actual number is not very important since collisions are only likely to occur when two or more nodes are waiting for the cable to be idle). When a collision occurs, the sender will back off for a time defined by

$$t_{backoff} = \text{minimum frame size / data rate} \times R$$

where $R = \text{rand}(0, 2^K - 1)$ (discrete uniform distribution) and K is the number of collisions in a row (but maximum 10—there is no upper limit on the number of retransmissions, however). Note that for CSMA/CD, minimum frame size cannot be 0.

After waiting, the node will attempt to retransmit. In an example where two nodes are waiting for a third node to finish its transmission, they will first collide with probability 1, then with probability 1/2 ($K = 1$), then 1/4 ($K = 2$), and so on.

8.2 CSMA/AMP (CAN)

CSMA/AMP stands for Carrier Sense Multiple Access with Arbitration on Message Priority. If the network is busy, the sender will wait until it occurs to be free. If a collision occurs (again, if two transmissions are being started within 1 microsecond), the message with the highest priority (the lowest priority number) will continue to be transmitted. If two messages with the same priority seek transmission simultaneously, an arbitrary choice is made as to which is transmitted first. (In real CAN applications, all sending nodes have a unique identifier, which serves as the message priority.)

8.3 Round Robin (Token Bus)

The nodes in the network take turns (from lowest to highest node number) to transmit one frame each. Between turns, the network is idle for a time

$$t_{idle} = \text{minimum frame size / date rate},$$

representing the time to pass a token to the next node.

8.4 FDMA

FDMA stands for Frequency Division Multiple Access. The transmissions of the different nodes are completely independent and no collisions can occur. In this mode, there is an extra attribute

Bandwidth allocations A vector of shares for the sender nodes which must sum to at most one.

The actual bit rate of a sender is computed as (allocated bandwidth × data rate).

8.5 TDMA (TTP)

TDMA stands for Time Division Multiple Access. Works similar to FDMA, except that each node has 100 % of the bandwidth but only in its scheduled slots. If a full frame cannot be transmitted in a slot, the transmission will continue in the next scheduled slot, without any extra penalty. Note that overhead is added to each frame just as in the other protocols. The extra attributes are

Slot size (bits) The size of a sending slot. The slot time is hence given by

$$t_{slot} = \text{slot size / data rate.}$$

Schedule A vector of sender node ID's (1 ... nbrOfNodes) specifying a cyclic send schedule. A zero is also an allowed node ID, meaning that no-one is allowed to transmit in that time slot.

8.6 Switched Ethernet

In Switched Ethernet, each node in the network has its own, full-duplex connection to a central switch. Compared to an ordinary Ethernet, there will never be any collisions on the network segments in a Switched Ethernet. The switch stores the received messages in a buffer and then forwards them to the correct destination nodes. This common scheme is known as *store and forward*.

If many messages in the switch are destined for the same node, they are transmitted in FIFO order. There can be either one queue that holds all the messages in the switch, or one queue for each output segment. In case of heavy traffic and long message queues, the switch may run out of memory. The following options are associated with the Switched Ethernet:

Total switch memory (bits) This is the total amount of memory available for storing messages in the switch. An amount of memory equal to the length of the message is allocated when the message has been fully received in the switch. The same memory is deallocated when the complete message has reached its final destination node.

Switch buffer type This setting describes how the memory is allocated in the switch. *Common buffer* means that all messages are stored in a single FIFO queue and share the same memory area. *Symmetric output buffers* means that the memory is divided into *n* equal parts, one for each output segment connected to the switch. When one output queue runs out of memory, no more messages can be stored in that particular queue.

Switch overflow behavior This option describes what happens when the switch has run out of memory. When the complete message has been received in the switch, it is deleted. *Retransmit* means that the switch then informs the sending node that it should try to retransmit the message. *Drop* means that no notification is given—the message is simply deleted.

8.7 FlexRay

In FlexRay the transmission cycle consists of three consecutive segments. The first, *static*, segment works similar to the TDMA protocol. The nodes take turns to transmit data according to a schedule. A node can only transmit when it is scheduled to do so. If the node has nothing to transmit, the network is idle until it is time to change node according to the schedule.

The second, *dynamic*, segment is divided into a number of small mini-slots with a corresponding schedule. In each mini-slot the scheduled node may start to transmit but only if the transmission is finished before the end of the dynamic segment. The transmission can, unlike in the static segment, continue to transmit when the mini-slot is over. If the scheduled node was nothing to transmit, the network will be idle the time it takes to transmit a frame the size of a mini-slot. Note that a message can be too large to ever be transmitted and thus blocks the sending node for transmitting messages in the dynamic segment.

The third, *idle*, segment where the network can't transmit anything. This segment is used to simulate both the symbol window and the network idle time in FlexRay.

The FlexRay protocol has the following extra parameters:

Slotsize (bits) Size of a slot for the static segment.

Static schedule Transmission schedule for the static segment.

Dynamic schedule Transmission schedule for the dynamic segment.

Mini slot size (bits) Size of a mini-slot for the dynamic segment.

Network idle time (bits) Size of the idle segment

The static segment is length(Static schedule)*Slotsize/dataRate seconds long and the dynamic segment will similarly be length(Dynamic schedule)*Minislotsize/dataRate seconds long. The network will then be idle for networkIdle/dataRate seconds. Additionally, both senders have an extra field where it is specified wheter the message should be transmitted in the static or in the dynamic segment.

8.8 PROFINET IO

The PROFINET IO send cycle consists of three intervals, synchroniztion, RT Class 3 and RT Class 1/NRT. RT Class 2 is not supported in this implementation.

Synchronization During the synchronization interval no node can send or receive messages. The duration of the synchronization interval is $\frac{\textbf{Synchronization length}}{\textbf{Datarate}}$ seconds.

RT Class 3 / IRT Following the synchronization interval is the *RT Class 3 / IRT (Isochronous Real Time)* interval. The transmissions during the are determined by the **IRT schedule**. The schedule is represented as a matrix with 5 columns and as many rows as messages to be sent during an IRT-interval. The first column specifies the ID of the message that should be transmitted. The message ID should be an integer larger than zero. The second and third column specifies from which node the message should be sent from and sent to respectively. The fourth column specifies the time, in seconds, when the message should be sent relative the start of the IRT interval. The fifth column specifies how long time it takes to propagate the message from sender to receiver.

The latest incoming message in each node is saved and is retransmitted in each the IRT interval.

Broadcasting is not supported in the IRT interval.

RT Class 1/NRT The third and final interval is the *RT Class 1 / NRT (Non Real Time)* interval. The length of the interval is determined by the user by setting the **NRT length [bits]** parameter. In the field labeled Node connection graph, the user has to specify how the different nodes are connected. The **Node connection graph** should be represented as a square matrix with the same number of rows and column as there are nodes in the network. Each element (x, y) in the matrix represents to which node a message, currently in node x, should be transmitted to on its way to node y. This way all messages will be transmitted in a deterministic fashion even if there exists multiple possible paths from the sending to the receiving node in the network.

Each node is considered to have 4 ports and can thus be connected to 4 or less other nodes. An incoming message is considered to be a NRT message if it's ID is equal to zero.

If a message is being transmitted to a node that has an empty switch queue the message will cut-through this node. This means that only the address bits will be read before the node with the empty switch start to transmit the message. The address is considered being composed of the first 114 bits.

PROFINET IO offers the possibility to sort queues by priority instead of FIFO. This protocol shares two parameter fields with Switched Ethernet; Total switch memory and Switch overflow behavior.

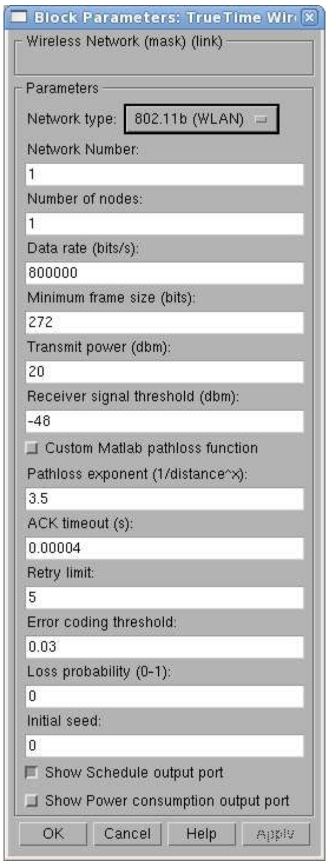

Block Parameters: TrueTime Wir
Wireless Network (mask) (link)
Parameters
Network type: 802.11b (WLAN)
Network Number: 1
Number of nodes: 1
Data rate (bits/s): 800000
Minimum frame size (bits): 272
Transmit power (dbm): 20
Receiver signal threshold (dbm): -48
☐ Custom Matlab pathloss function
Pathloss exponent (1/distance^x): 3.5
ACK timeout (s): 0.00004
Retry limit: 5
Error coding threshold: 0.03
Loss probability (0-1): 0
Initial seed: 0
☐ Show Schedule output port
☐ Show Power consumption output port

Figure 7 The dialog of the TrueTime wireless network block.

9. The TrueTime Wireless Network

The usage of the wireless network block is similar to and works in the same way as the wired one. To also take the path-loss of the radio signals into account, it has `x` and `y` inputs to specify the true location of the nodes. Two network protocols are supported at this moment: IEEE 802.11b/g (WLAN) and IEEE 802.15.4 (ZigBee). Some more technical details about the wireless network can be found in [Ohlin, 2006]. The radio model used includes support for:

- Ad-hoc wireless networks.
- Isotropic antenna.
- Inability to send and receive messages at the same time.
- Path loss of radio signals modeled as $\frac{1}{d^a}$ where d is the distance in meters and a is a parameter chosen to model the environment.
- Interference from other terminals.

The wireless network block is configured through the block mask dialog, see Figure 7. Some parameters can also be set on a per node basis with the command `ttSetNetworkParameter`. The following parameters are common to all models:

Network type Determines the MAC protocol to be used. Can be either 802.11b/g (WLAN) or 802.15.4 (ZigBee).

Network number The number of the network block. The networks must be numbered from 1 and upwards. Wired and wireless networks are not allowed to use the same number.

Number of nodes The number of nodes that are connected to the network. This number will determine the size of the `Snd`, `Rcv` and `Schedule` input and outputs of the block.

Data rate (bits/s) The speed of the network.

Minimum frame size (bits) A message or frame shorter than this will be padded to give the minimum length. Denotes the minimum frame size, including any overhead introduced by the protocol. E.g., most network protocols have a fixed number of header and tail bits, so the frame must be at least $sizeof(header) + sizeof(tail)$ long.

Transmit power Determines how strong the radio signal will be, and thereby how long it will reach.

Receiver signal threshold If the received energy is above this threshold, then the medium is accounted as busy.

Path-loss exponent The path loss of the radio signal is modeled as $\frac{1}{d^a}$ where d is the distance in meters and a is a suitably chosen parameter to model the environment. Typically chosen in the interval 2-4.

ACK timeout The time a sending node will wait for an ACK message before concluding that the message was lost and retransmit it.

Retry limit The maximum number of times a node will try to retransmit a message before giving up.

Error coding threshold A number in the interval $[0, 1]$ which defines the percentage of block errors in a message that the coding can handle. For example, certain coding schemes can fully reconstruct a message if it has less than 3% block errors. The number of block errors are calculated using the signal-to-noise ratio, where the noise is all other ongoing transmissions.

9.1 802.11b/g (WLAN)

IEEE 802.11b/g is used in many laptops and mobile devices of today. The protocol is based on CSMA/CA with some modifications.

In the simulation, a package transmission is modeled like this: The node that wants to transmit a packet checks to see if the medium is idle. The transmission may proceed, if the medium is found to be idle, and has stayed so for 50 μs. If, on the other hand, the medium is found to be busy, a random back-off time is chosen and decremented in the same way as when colliding (described later in this section). When a node starts to transmit, its relative position to all other nodes in the same network is calculated, and the signal level in all those nodes are calculated according to the path-loss formula $\frac{1}{d^a}$.

The signal is assumed to be possible to detect if the signal level in the receiving node is larger than the **receiver signal threshold**. If this is the case, then the signal-to-noise ratio (SNR) is calculated and used to find the block error rate (BLER). Note that all other transmissions add to the background noise when calculating the SNR. The BLER, together with the size of the message, is used to calculate the number of bit errors in the message and if the percentage of bit errors is lower than the **error coding threshold**, then it is assumed that the channel coding scheme is able to fully reconstruct the message. If there are (already) ongoing transmissions from other nodes to the receiving node and their respective SNRs are lower than the new one, then all those messages are marked as collided. Also, if there are other ongoing transmissions which the currently sending node reaches with its transmission, then those messages may be marked as collided as well.

Note that a sending node does not know if its message is colliding, therefore ACK messages are sent on the MAC protocol layer. From the perspective of the sending node, lost messages and message collisions are the same, i.e., no ACK is received. If no ACK is received during **ACK timeout**, the message is retransmitted after waiting a random back-off time within a contention window. The contention window size is doubled for every retransmission of a certain message. The back-off timer is stopped if the medium is busy, or if it has not been idle for at least 50 μs. There are only **Retry limit** number of retransmissions before the sender gives up on the message and it is not retransmitted anymore.

9.2 802.15.4 (ZigBee)

ZigBee is a protocol designed with sensor and simple control networks in mind. It has a rather low bandwidth, but also a really low power consumption. Although it is based on CSMA/CA as 802.11b/g, it is much simpler and the protocols are not the same.

The packet transmission model in ZigBee is similar to WLAN, but the MAC procedure differ and is modeled as:

```
1. Initialize:
   NB=0
   BE=macMinBE
2. Delay for a random number of backoff periods in the interval $[0, 2^{BE} - 1]$
3. Is the medium idle?
       if yes: send
       else: goto 4
4. Update the backoff counters:
   NB=NB+1
   BE=min(BE+1, aMaxBE)
5. Is NB>macMaxCSMABackoffs?
       if yes: drop the packet
       else: goto 2
```

The variable names are taken from the standard to make comparisons easier. A small explanation of their names is provided below.

NB Number of backoffs.

BE Backoff exponent.

macMinBE The minimum value of the backoff exponent in the CSMA/CA algorithm. The default value is 3.

aMaxBE The maximum value of the backoff exponent in the CSMA/CA algorithm. The default value is 5.

macMaxCSMABackoffs The maximum number of backoffs the CSMA/CA algorithm will attempt before declaring a channel access failure. The default value is 4.

9.3 Calculation of Error Probabilities

During the calculation of error probabilities, it is for simplicity assumed that BPSK[1] is always used in the transmissions. This is of course an approximation, but it relates well to reality.

Assume that a symbol is sent, in our case this is a bit, i.e., a 0 or a 1. Additive white Gaussian noise gives a probability density function for the received symbol, that for some signal-to-noise ratio may look like Figure 8. A threshold is then used to decide if the received symbol is a 0 or a 1. The decision threshold is marked as a line in the middle of the figure. The darker area to the left of the threshold gives the probability of a symbol error. A higher signal to noise ratio translates the curve to the right, making the probability of error smaller.

The above standard procedure should ideally be performed for every bit in the message. The total number of calculated bit errors should then be compared to the error coding threshold. This is, however, not done, because it would be very computationally expensive. Instead, the maximum noise level during the transmission is saved, and used to calculate the worst case SNR. By assuming that bit errors in a message are uncorrelated, it is deduced that the number of bit errors, X, belongs to a binomial distribution $X \in Bin(n,p)$, where n is the number of bits in the message, and p is the probability that a certain bit is erroneous. If the value of n is large, the binomial distribution can be approximated with a normal distribution, using the central limit theorem. This gives that $X \in N(np, \sqrt{npq})$ where $q = 1 - p$. What we are really interested in is the probability that bn, where b is the error coding threshold, is larger than the total number of bit errors in a message. This probability is calculated using

$$P(X \leq bn) = \begin{cases} \Phi(\frac{bn - np}{\sqrt{npq}}) & \text{if} \quad bn - np > 0 \\ 1 - \Phi(\frac{|bn - np|}{\sqrt{npq}}) & \text{if} \quad bn - np \leq 0 \end{cases}$$

where Φ is the standard normal cumulative distribution function.

Example Assume that a message consists of 100 bits, i.e., $n = 100$. The probability that a certain bit is erroneous has been calculated to 0.1 using the above method, i.e., $p = 0.1$ and $q = 1 - p = 0.9$. The error coding threshold has been set to 5%, i.e., $b = 0.05$. Then the probability that we can decode the complete message is

$$P(X \leq bn) = 1 - \Phi(\frac{|bn - np|}{\sqrt{npq}}) = 1 - \Phi(\frac{5}{\sqrt{9}}) \approx 0.0478$$

[1]Binary Phase Shift Keying (BPSK) is a means of transmitting symbols by altering the phase of a reference signal. It uses two phases separated by 180° and is hence binary.

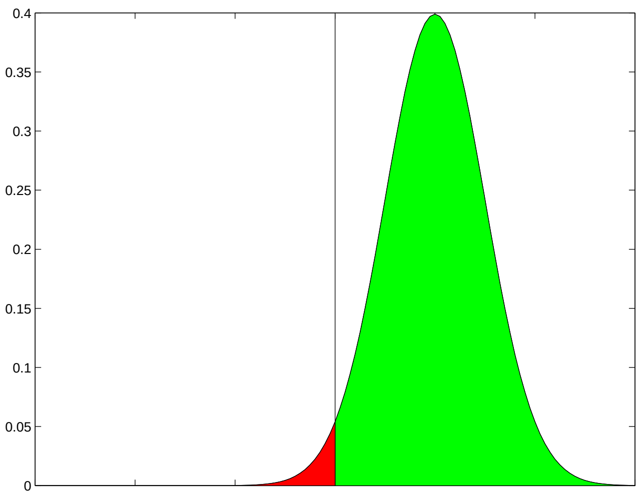


Figure 8 Probability density function for a received symbol when using binary phase shift keying and additive white Gaussian noise. The line in the middle is the decision threshold. The area to the left of the threshold gives the probability of an erroneous decision. The area to the right gives the probability of a correct decision.

9.4 User-Defined Path-Loss Function

The default path-loss function (or propagation model) used in the TrueTime wireless simulations is

$$P_{receiver} = \frac{1}{d^a} P_{sender}$$

where P is the power, d is the distance in meters, and a is a parameter that can be chosen to model different environments. This model is often used in simulations, but in some cases it can be advantageous to use other models. TrueTime has the possibility to register a user-defined path-loss function. The function is written as a Matlab function (M-file or MEX-function) and can therefore take advantage of all the built-in functions available in Matlab. In particular, this includes the possibility to use persistent variables, i.e., variables which are retained in memory between calls to the function. The function can, for example, be used to model a Rayleigh[2] fading or the blocking of radio signals to and from certain points in the environment. At the moment, nodes in the TrueTime framework only have x and y coordinates, but if a direction was to be introduced this function could also be used to model directive effects in the antenna behaviour.

The Matlab function takes the following arguments

- Transmission power
- Name of the sending node
- x and y coordinates of the sending node
- Name of the receiving node
- x and y coordinates of the receiving node
- Current simulation time

[2]In a Rayleigh fading, the relative speed of two nodes and the number of multiple paths that the signal takes from the sender to the receiver is taken into account. See Figure 9 for an example.

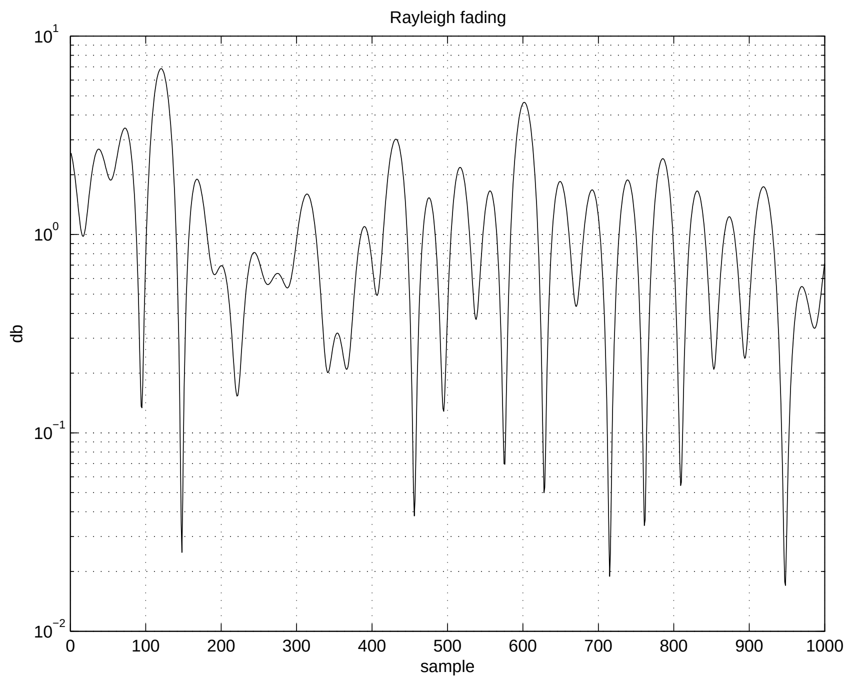


Figure 9 Example of a Rayleigh fading using a radio frequency of 2.4 MHz. Nodes moving with a relative speed of 6 km/h, 1 second sampling interval and 10 random phasers.

and returns the signal power in the receiving node.

A small example showing the structure of how a Rayleigh fading could be implemented can be seen in Listing 6.

To increase simulation speed, it is recommended to implement the Matlab function as a C MEX-function.

Listing 6 Example of path-loss function modeling Rayleigh fading.

```
function power = rayleigh(transmitPower, node1, x1, y1, node2, x2, y2, time)

% Calculate the exponential pathloss
distance = sqrt((x1 - x2)^2 + (y1 - y2)^2);
power = transmitPower/(distance+1)^3.5;

% Kalman filter to get the relative velocity of the two nodes
velocity = kalman_velocity(node1, x1, y1, node2, x2, y2, time);
% Calculate the rayleigh fading
factor = calculate_rayleigh(node1, node2, velocity, time);

% Add the rayleigh fading to the exponential path loss
power = power * factor;
```

10. The TrueTime Battery

The battery block has one parameter, the initial power, which can be set using the configuration mask. To use the battery, enable the check box in the kernel configuration mask and connect the output of the battery to the `E` input of the kernel block. Connect every power drain such as the `P` output of the kernel block, ordinary Simulink models, and the wireless network block to the `P` input of the battery. The battery uses a simple integrator model, so it can be both charged and recharged.

Note that the kernel will not execute any code if it is configured to use batteries and the input `P` to the kernel block is zero. See the example in Section 12.4 below for more details on the use of TrueTime batteries.

11. The TrueTime Standalone Network Blocks

The standalone network blocks, named TrueTime Send and TrueTime Receive, as seen in Figure 1, can be used to send messages using the network blocks without using kernel blocks. This makes it possible to create TrueTime network simulations without having to initialize kernels, create and install interrupt handlers, etc. It is in other words possible to create a whole network simulation in Simulink without any M-files at all. It is also possible to mix these blocks with kernel blocks, so that some stations use the standalone network blocks, while others use the standard `ttSend` and `ttGetMsg` primitives from within a code function executing in a kernel block.

The standalone network blocks are configured through the block mask dialogs, seen in Figure 10. The parameters are the same that are used in the TrueTime Send and TrueTime Receive primitives. The TrueTime Send block has a Simulink trigger input port, which can be configured to trigger on raising, falling or either flanks. The `ttGetMsg` block has an optional trigger output port. The value of the trigger output switches back and forth between 0 and 1 as messages are received. This port can be used to trigger something that should be executed after a new message has been received.

12. Examples

The directory `$DIR/examples` contains ten examples:

`simple`	Several different ways of implementing a simple periodic controller are demonstrated. Both M-file and C++ implementations are provided.
`threeservos`	Illustrates task scheduling and control, where three periodic control tasks execute on the same CPU. Both M-file and C++ implementations are provided.
`networked`	Demonstrates networked control involving four computer nodes and the wired network block. Both M-file and C++ implementations are provided, as well as an implementation using the stand-alone network interface blocks.

`wireless`	Demonstrates wireless networked control with transmission power control to minimize the energy consumption. M-file implementation only.
`AODV`	Illustrates how higher-layer communication protocols such as AODV routing can be implemented in TrueTime. M-file implementation only.
`soccer`	A larger example showing simulation and animation of ten mobile robots playing soccer. M-file implementation only.
`RUNES_demo`	A very large example with mobile robot navigation through a sensor network using ultrasound trilateration. C++ implementation only.

The first three examples are provided in both Matlab and C++ versions. However, the descriptions below will only treat the Matlab case. For detailed instructions on how to compile the examples, see the README-files in the corresponding example directories.

12.1 PID-control of a DC-servo

Introduction The first example considers simple PID control of a DC-servo process, and is intended to give a basic introduction to the TrueTime simulation environment. The process is controlled by a controller task implemented in a TrueTime kernel block. Four different implementations of the controller task are provided to show different ways to implement periodic activities. The files are found in the directory `$DIR/examples/simple/matlab`.

Process and Controller The DC-servo is described by the continuous-time transfer function

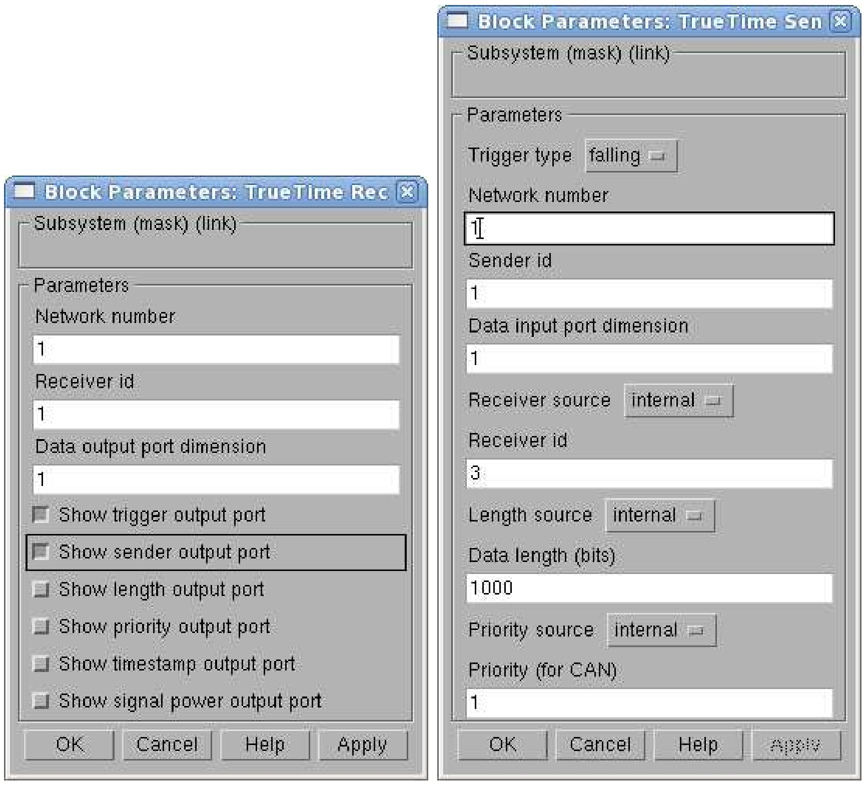
$$G(s) = \frac{1000}{s(s+1)} \tag{1}$$

The PID-controller is implemented according to the following equations

$$\begin{aligned} P(k) &= K \cdot (\beta r(k) - y(k)) \\ I(k+1) &= I(k) + \frac{Kh}{T_i}(r(k) - y(k)) \\ D(k) &= a_d D(k-1) + b_d(y(k-1) - y(k)) \\ u(k) &= P(k) + I(k) + D(k) \end{aligned} \tag{2}$$

where $a_d = \frac{T_d}{Nh+T_d}$ and $b_d = \frac{NKT_d}{Nh+T_d}$, see [Åström and Hägglund, 1995]. The controller parameters were chosen to give the system a closed-loop bandwidth of $\omega_c = 20$ rad/s and a relative damping of $\zeta = 0.7$.

Simulation Files The initialization script (`servo_init.m`) is given in an abbreviated version in Listing 7. As seen in the initialization script, it is possible to choose between four different implementations of the periodic control task. They are specified by the init function parameter in the kernel block dialog.


Block Parameters: TrueTime Rec

Subsystem (mask) (link)

Parameters

Network number: 1

Receiver id: 1

Data output port dimension: 1

- [✓] Show trigger output port
- [✓] Show sender output port
- [ ] Show length output port
- [ ] Show priority output port
- [ ] Show timestamp output port
- [ ] Show signal power output port

OK | Cancel | Help | Apply

Block Parameters: TrueTime Sen

Subsystem (mask) (link)

Parameters

Trigger type: falling

Network number: 1

Sender id: 1

Data input port dimension: 1

Receiver source: internal

Receiver id: 3

Length source: internal

Data length (bits): 1000

Priority source: internal

Priority (for CAN): 1

OK | Cancel | Help | Apply

Figure 10 The dialog of the TrueTime Send block to the left, and the dialog of the TrueTime Receive block to the right.

- *Implementation 1*: Uses the TrueTime built-in support for periodic tasks, and the code function is given in the file `pidcode1.m`.
- *Implementation 2*: Also uses the TrueTime built-in support for periodic tasks, but the computation of the control signal in each sample is done by calling a Simulink block diagram. The code function is given in the file `pidcode2.m`. Since all the controller parameters and states are contained in the Simulink block, the task data (`data2`) only consist of the control signal, u.
- *Implementation 3*: Implements the periodic task by using the TrueTime primitive `ttSleepUntil`. The code function is given in the file `pidcode3.m`.
- *Implementation 4*: Implements the periodic task by using a periodic timer. The associated interrupt handler samples the process and triggers task jobs. The handler and controller task communicate using a mailbox. The code functions for the handler and controller are given in the files `sampler code.m` and `pidcode4.m`, respectively.

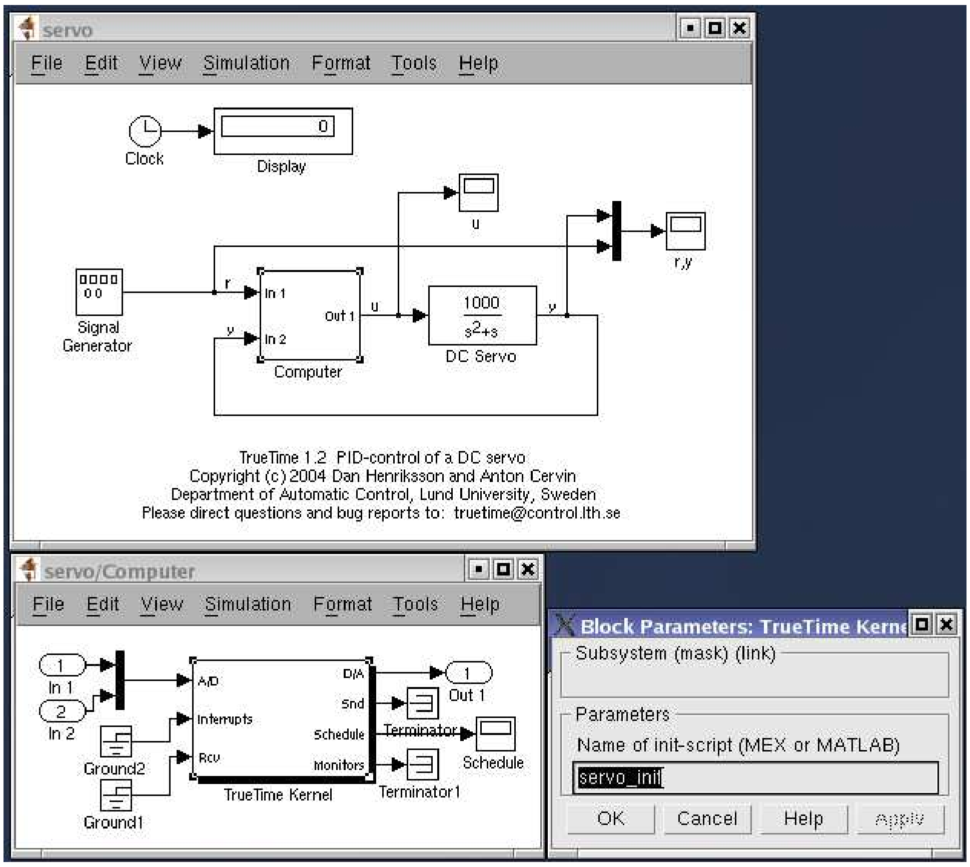
Simulations The Simulink model is called `servo.mdl` and is given in Figure 11. Open the Simulink model and try the following

- Run a simulation and verify that the controller behaves as expected. Notice the computational delay of 2 ms in the control signal. Compare with the code function, `pidcode1.m`. Study the schedule plot (high=running, medium=ready, low=idle).

- Try changing the execution time of the first segment of the code function, to simulate the effect of different input-output delays.
- Change the sampling period and study the resulting control performance.
- A PID-controller is implemented in the Simulink block `controller.mdl`. Change the init function parameter of the kernel block from 1 to 2, so that implementation 2 is used instead of 1. Study the corresponding code function, `pidcode2.m`. This code function is using the Simulink block to compute the control signal in each sample.
- Change to implementation 3 and run a simulation. Study the code function,

Listing 7 The initialization script for the PID-control example.

```
  function servo_init(mode)

  ttInitKernel(2, 1, 'prioFP'); % nbrOfInputs, nbrOfOutputs, fixed priority

  period = 0.006;
  deadline = period;
  offset = 0.0;
  prio = 1;

  data.K = 0.96;
  ... % more task data

switch mode,
 case 1,
  % IMPLEMENTATION 1: using the built-in support for periodic tasks
  %
  ttCreatePeriodicTask('pid_task',offset,period,prio,'pidcode1',data);

 case 2,
  % IMPLEMENTATION 2: calling Simulink block within code function
  %
  data2.u = 0;
  ttCreatePeriodicTask('pid_task',offset,period,prio,'pidcode2',data2);

 case 3,
  % IMPLEMENTATION 3: sleepUntil and loop back

  data.t = 0;
  ttCreateTask('pid_task',deadline,prio,'pidcode3',data);
  ttCreateJob('pid_task');

 case 4,
  % IMPLEMENTATION 4: sampling in timer handler, triggers task job

  hdl_data.yChan = 2;
  ttCreateInterruptHandler('timer_handler',prio,'samplercode',hdl_data);
  ttCreatePeriodicTimer('timer',offset,period,'timer_handler');
  ttCreateMailbox('Samples',10);
  ttCreateTask('pid_task',deadline,prio,'pidcode4',data);
end
```



TrueTime 1.2 PID-control of a DC servo
Copyright (c) 2004 Dan Henriksson and Anton Cervin
Department of Automatic Control, Lund University, Sweden
Please direct questions and bug reports to: truetime@control.lth.se

Name of init-script (MEX or MATLAB)
servo_init

Figure 11 The TrueTime model of the DC-servo system.

`pidcode3.m`.

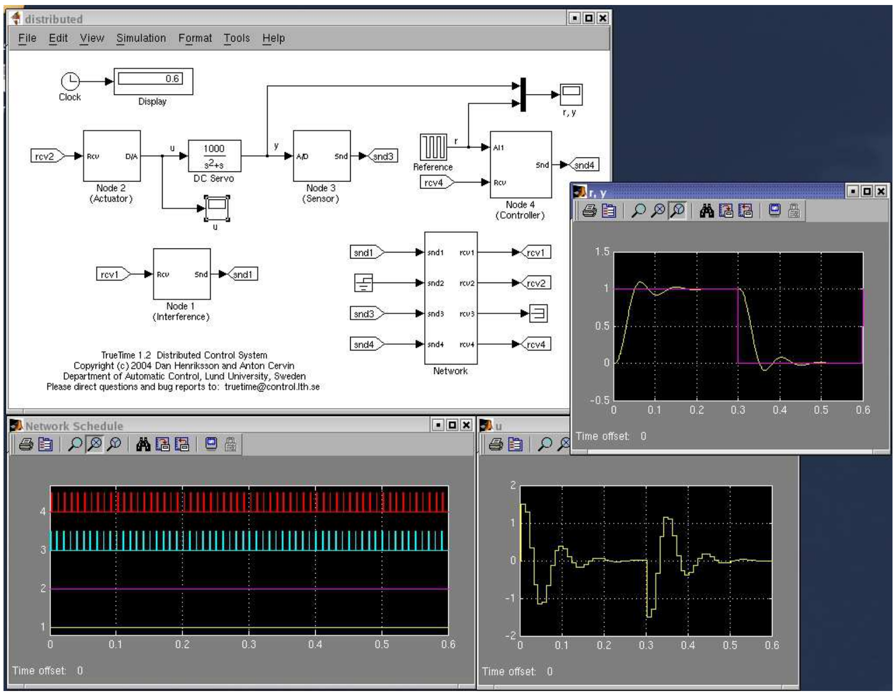
- Change to implementation 4 and run a simulation. Study the code functions, `samplercode.m` and `pidcode4.m`. Notice the inclusion of the handler in the schedule plot.

12.2 Task Scheduling and Control

Introduction This example extends the simple PID control example from the previous section to the case of three PID-tasks running concurrently on the same CPU controlling three different DC-servo systems. The effect of the scheduling policy on the global control performance is demonstrated. The files are found in the directory `$DIR/examples/threeservos/matlab`.

Simulations Open the Simulink model `threeservos.mdl` and try the following

- Make sure that rate-monotonic scheduling is specified by the function `ttInitKernel` in the initialization script (`threeservos_init.m`) and simulate the system. Study the computer schedule and the control performance. Task 1 will miss all its deadlines and the corresponding control loop is unstable.
- Change the scheduling policy to earliest-deadline-first (change `'prioRM'` to `'prioEDF'`) and run a new simulation. Again study the computer schedule



TrueTime 1.2 Distributed Control System
Copyright (c) 2004 Dan Henriksson and Anton Cervin
Department of Automatic Control, Lund University, Sweden
Please direct questions and bug reports to: truetime@control.lth.se

Figure 12 The TRUETIME model of the networked control system.

and the control performance. After an initial transient all tasks will miss their deadlines, but still the overall control performance is satisfactory.

12.3 Networked Control System

Introduction This example simulates networked control of the DC-servo of Equation (1). The example contains four computer nodes, each represented by a TRUETIME kernel block. A time-driven sensor node samples the process periodically and sends the samples over the network to the controller node. The control task in this node calculates the control signal and sends the result to the actuator node, where it is subsequently actuated. The simulation also involves an interfering node sending disturbing traffic over the network, and a disturbing high-priority task executing in the controller node. The files are found in the directory `$DIR/examples/networked/matlab`.

Simulations The Simulink model is called `networked.mdl` and is given in Figure 12. Open the Simulink model and try the following

- Study the initialization scripts and code functions for the different nodes. The event-driven nodes contain interrupt handlers, which are activated as messages arrive over the network. The handler then triggers the task that will read and process the message.
- Run a first simulation without disturbing traffic and without interference in the controller node. This is obtained by setting the variable `BWshare` in the code function of the interfering node (`interfcode.m`) to zero, and by commenting out the creation of the task `'dummy'` in `controller_init`. In this case we will get a constant round-trip delay and satisfactory control

performance. Study the network schedule (high=sending, medium=waiting, low=idle) and the resulting control performance.

- Switch on the disturbing node and the interfering task in the controller node. Set the variable `BWshare` to the percentage of the network bandwidth to be used by the disturbing node. Again study the network schedule and the resulting control performance. Experiment with different network protocols and different scheduling policies in the controller node.

12.4 Wireless Control System with Automatic Gain Control

Introduction This example shows networked control of a DC-servo described by Equation (1) using communication over a wireless network. The example also shows how to simulate power consumption and how to use the battery block. The model contains two computer nodes located 20 m apart, each represented by a TRUETIME kernel and battery block. A time-driven sensor/actuator node samples the process periodically and sends the samples over the network to the controller node. The control task in this node calculates the control signal and sends the result back to the sensor/actuator node, where it is actuated. The wireless communication link is at the same time subject to a simple power control scheme. Power control tasks running in both the sensor/actuator node and in the controller node periodically send out ping messages to the other node to test the channel transmission. If a reply is received, the channel is assumed to be good and the transmission power is lowered. If on the other hand no reply is received, then the transmission power is considerably increased until it saturates or a reply is received again. The files are found in the directory `$DIR/examples/wireless`.

Simulations Open the model `wireless.mdl` to run the simulation.

- Run a first simulation without modifying anything. Look at the plots showing the battery levels in the two nodes. Note that the power control scheme is not activated until 2 seconds have elapsed. Also note how the measured values at some times deviate more than usual from the reference values. This deviation is caused by the fact that it is possible to lose several consecutive sensor value readings when using the simple power control that is implemented in the nodes.
- Switch off the power control scheme in the controller node. This is done by commenting out the creation of the task `power_controller_task` in `controller_init`. Run the simulation again and now note that the power drain is constant in the controller node. This causes the battery to run out of energy and the control is lost.
- Experiment with different network parameters and protocols and see how it affects the control behaviour. In this example, the kernel block is set to consume 10 mW. This can easily be changed by using the command `ttSetKernelParameter`. This command can also be used to set the CPU scaling factor to enable Dynamic Voltage Scaling.

12.5 Wireless Ad-hoc Routing Using AODV

Introduction The TrueTime wireless network simulates communication in an ad-hoc network, i.e., no centralized access point or infrastructure exists to coordinate the traffic across the network. In such networks it is necessary to implement decentralized functionality to be able to route the traffic over the network. This example describes a TrueTime implementation of one such ad-hoc wireless routing protocol.

AODV [Perkins and Royer, 1999] stands for Ad-hoc On-Demand Distance Vector routing and contrary to most routing mechanisms, it does not rely on periodic transmission of routing messages between the nodes. Instead, routes are created on-demand, i.e., only when actually needed to send traffic between a source and a destination node. This leads to a substantial decrease in the amount of network bandwidth consumed to establish routes. Below follows a brief description of the functionality of AODV. For a complete definition of the AODV protocol, see [Perkins and Royer, 2003].

AODV uses three basic types of control messages in order to build and invalidate routes: route request (RREQ), route reply (RREP), and route error (RERR) messages. These control messages contain source and destination sequence numbers, which are used to ensure fresh and loop-free routes.

A node that requires a route to a destination node initiates route discovery by broadcasting an RREQ message to its neighbors. A node receiving an RREQ starts by updating its routing information backwards towards the source. If the same RREQ has not been received before, the node then checks its routing table for a route to the destination. If a route exists with a sequence number greater than or equal to that contained in the RREQ, an RREP message is sent back towards the source. Otherwise, the node rebroadcasts the RREQ. When an RREP has propagated back to the original source node, the established route may be used to send data. Periodic hello messages are used to maintain local connectiviy information between neighboring nodes. A node that detects a link break will check its routing table to find all routes which use the broken link as the next hop. In order to propagate the information about the broken link, an RERR message is then sent to each node that constitute a previous hop on any of these routes.

The files for this tutorial example are found in the directory `$DIR/examples/AODV`. All nodes are initialized using the same initialization script, `node_init.m`. Two TrueTime tasks are created in each node to handle AODV send and receive actions, respectively. The AODV send task is activated from the application code as a data message should be sent to another node in the network. The AODV receive task handles incoming AODV control messages and forwarding of data messages. Communication between the application layer and the AODV layer is handled using TrueTime mailboxes.

The AODV send task (`AODVsendcode.m`) operates according to the following code:

```
IF (data message received from application)
   check the routing table for a route to the destination;
   IF (a valid route exists)
      forward data message to next hop on route;
      update expiry time of route entry;
   ELSE
      initiate route discovery by broadcasting RREQ message;
      buffer data message until route has been established;
   END
ELSE IF (notified of established new route)
   send all buffered data messages to destination
END
```

The AODV receive task (`AODVrcvcode.m`) performs the following:

```
IF (receiving data message)
   update expiry timer for reverse route entry to source;
   IF (this node is the destination)
      Pass data message to application;
   ELSE
      forward data message to next hop on route;
      update expiry timer of route entry;
   END
ELSE
   SWITCH message_type
      CASE RREQ:
         IF (first time this RREQ is received)
            enter RREQ in cache;
            create or update route entry to source;
            check the routing table for a route to the destination;
            IF (a route exists)
               send RREP message back towards source;
            ELSE
               update and rebroadcast the RREQ;
            END
         END
      CASE RREP:
         check the routing table for a route to the destination;
            IF (no route exists)
               create route entry to destination;
            ELSE IF (route entry exists but should be updated)
               update route entry to destination;
            END
            IF (this node is the original source)
               notify the AODV send task about the new route;
            ELSE IF (route to destination was created or updated)
               update reverse route entry towards source;
               propagate RREP to next hop towards source;
            END
      CASE RERR:
            find and invalidate all affected route entries;
            propagate the RERR to all previous hops on the routes;
   END
END
```

Each node also contains a periodic task (`hellocode.m`), responsible for broadcasting hello messages and determine local connectivity based on hello messages received from neighboring nodes. Finally, each node has a task to handle timer expiry of route entries (`expcode.m`).

Simulations Open the model AODV.mdl to run the simulation.

- The simulation example consists of seven nodes. Choose the option Update Diagram in the Edit menu to bring up an animation window of the simulation. This will show the original positions of the seven nodes and their respective signal reach.
- Run a simulation. In the simulation scenario, the left-most node (node 1) sends data periodically to node 7 with period 0.5. The initial route that is established is $1 \rightarrow 3 \rightarrow 5 \rightarrow 7$. At time $t = 3$, node 5 starts to move which eventually leads to the route breaking. At time $t = 10$, node 6 repairs the route by moving in between node 4 and 7. The printouts in the Matlab command window describe the actions in the AODV layer in more detail. Also study the global variable `routing_table`.
- Open and examine the file `initsim.m`. This file initializes the global variables used in the simulation, e.g., the routing table and the node positions. By changing the variable `verbose` from 0 to 1 even more detailed AODV information will be displayed when the simulation is run.
- The global variables `sent` and `received` show the data that is sent (by node 1) and received (by node 7) in the simulation. Examine the lengths of these vectors to determine how many messages that where lost due to the delay in detecting and propagating the information about the broken link back to the source node. (Answer: The messages sent at times 8.0002, 8.5002, and 9.0002 are lost.)
- The hello interval determines who fast the network will respond to broken links (and also the bandwidth overhead). Try changing the AODV parameter `HELLO_INTERVAL` (both in `initsim.m` and `node_init.m`) to decrease the number of lost data messages. In this case only two messages are lost.

12.6 Mote Soccer

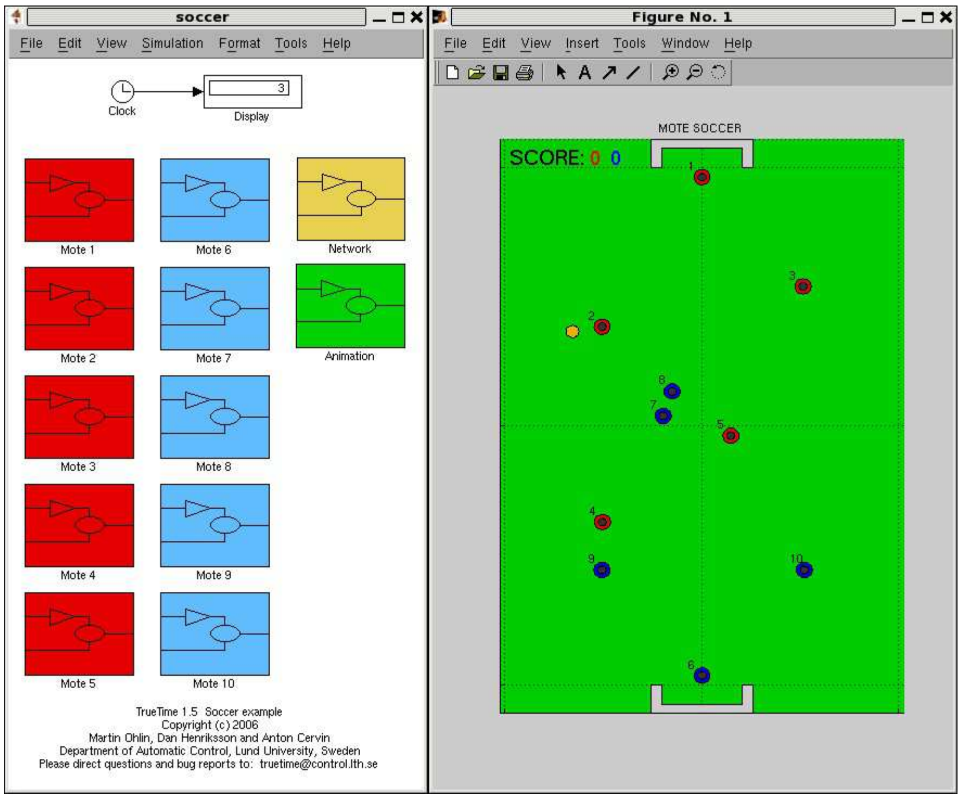
This largely undocumented example features a slighly more complex simulation set-up where ten mobile robots are playing soccer. The robots and the ball are animated during the simulation, see Figure 13. The simulation files are found in the directory `$DIR/examples/soccer`.

Each mobile robot (mote) is modeled using a kernel block and two integrators representing the x and y coordinates of the robot. The ball is modeled as a forth-order system (an integrator plus damping in each direction) implemented in an S-function (`ballmotion.m`). This S-function also handles the player interaction with the ball. The robots within each team communicate over the wireless network. The goalkeeper is each team acts as the "master" and coordinates the players.

The mask of the network block is programmed to dynamically change the contents of the underlying subsystem (study the initialization commands). This is a very conventient feature when working with a large number of network nodes.

13. Kernel Implementation Details

This section will give a brief description of the implementation of the TrueTime kernel. The main data structures will be described as well as the kernel imple-



TrueTime 1.5 Soccer example
Copyright (c) 2006
Martin Ohlin, Dan Henriksson and Anton Cervin
Department of Automatic Control, Lund University, Sweden
Please direct questions and bug reports to: truetime@control.lth.se

Figure 13 Mote soccer.

mentation. It will also be described how the event-based kernel simulation is achieved in Simulink, using the zero-crossing detection mechanism.

13.1 Kernel Data Structures

The main data structure of the TrueTime kernel is a C++ class called RTsys, see $DIR/kernel/ttkernel.h. An instance (rtsys) of this class is created in the initialization step of the kernel S-function. The rtsys object is stored in the UserData field of the kernel block between simulation steps. Among others, the RTsys class contains the following attributes:

```
class RTsys {
 public:
  double time;                // Current time in simulation

  double* inputs;             // Vector of input port values
  double* outputs;            // Vector of output port values

  Task* running;              // Currently running task

  List* readyQ;    // usertasks and handlers ready for execution, prio-sorted
  List* timeQ;     // usertasks and timers waiting for release, time-sorted

  List* taskList;    // A list containing all created tasks
  List* handlerList;
  List* monitorList;
  List* eventList;
  double (*prioFcn)(Task*); // Priority function
};
```

The ready queue and time queue are sorted linked list. The elements in the time queue (tasks and timers) are sorted according to release times and expiry times. A timer in the time queue is actually represented by its corresponding handler. The tasks in the ready queue are sorted according to the priority function `prioFcn`, which is a function that returns a (possibly dynamic) priority number from a `Task` instance, see the description of `ttInitKernel` in the command reference.

The `Task` class (`$DIR/kernel/task.h`) inherits from the `node` class of the linked list (`$DIR/kernel/linkedlist.h`) and contains the following basic attributes:

```
class Task : public Node {
 public:
  char* name;
  int segment;      // the current segment of the code function
  double execTime;  // the remaining execution time of the current segment

  void *data;       // task data (C++ case)
  char* dataMatlab; // name of global variable for task data (Matlab case)

  double (*codeFcn)(int, void*); // Code function (C++ case)
  char* codeFcnMatlab;  // Name of m-file code function (Matlab case)
};
```

The `exectime` of the running task is updated each time the kernel executes, see Listing 8. When it has reached zero, the next segment of the code function is executed. The task data in the Matlab case is represented as a name of a unique global variable. The code function of a task is represented either as a function pointer in the C++ case or the name of a Matlab m-file.

User tasks and interrupt handlers are both subclasses to `Task` and contain the attributes given below, among others. See `$DIR/kernel/usertask.h` and `$DIR/kernel/handler.h` for complete descriptions.

```
class UserTask : public Task {
public:
  double priority;
  double wcExecTime;
  double deadline;
  double absDeadline;
  double release;   // task release time if in timeQ
  double budget;

  int state;  // Task state (IDLE; WAITING; SLEEPING; READY; RUNNING)

  double tempPrio;  // temporarily raised prio value

  List *pending; // list of pending jobs

  InterruptHandler* deadlineORhandler; // deadline overrun handler
  InterruptHandler* exectimeORhandler; // execution-time overrun handler
  int nbrOfUserLogs;  // Number of user-created log entries
  Log* logs[NBRLOGS];

  void (*arrival_hook)(UserTask*);  // hooks
  void (*release_hook)(UserTask*);
  void (*start_hook)(UserTask*);
  void (*suspend_hook)(UserTask*);
  void (*resume_hook)(UserTask*);
  void (*finish_hook)(UserTask*);
};
```

The kernel implements priority inheritance to avoid priority inversion. Therefore each task has a dynamic priority value that may be raised while executing inside a monitor. Pending jobs are stored in the job queue of the task sorted by release time. See `$DIR/kernel/log.h` for the contents of the `Log` class.

```
class InterruptHandler : public Task {
 public:
  double priority;

  int type;  // {UNUSED, OVERRUN, TIMER, NETWORK, EXTERNAL}

  UserTask *usertask; // if overrun handler to task

  Timer* timer;       // if associated with timer interrupt

  Network* network;   // if associated with network receive interrupt

  Trigger* trigger;   // if associated with external interrupt
  int pending;        // list of pending invocations, if new external
                      // interrupt occurs before the old is served
};
```

See the corresponding header files in `$DIR/kernel` for the specifications of the classes `Timer`, `Network`, and `Trigger`.

13.2 Task Model

TrueTime user tasks may be periodic or aperiodic. Aperiodic tasks are triggered by the creation of task jobs, using the command `ttCreateJob`. All pending jobs are inserted in a job queue of the task sorted by release time. For periodic task (created by the command `ttCreatePeriodicTask`), an internal timer is set up to periodically create jobs for the task.

Apart from its code function, each task is characterized by a number of attributes. The static attributes of a task include

- a relative deadline
- a priority
- a worst-case execution time
- a period (if the task is periodic)

These attributes are kept constant throughout the simulation, unless explicitly changed by the user (see `ttSetX` in the command reference).

In addition to these attributes, each task job has dynamic attributes associated with it. These attributes are updated by the kernel as the simulation progresses, and include

- an absolute deadline
- a release time
- an execution time budget (by default equal to the worst-case execution time at the start of each task job)
- the remaining execution time

These attributes (except the remaining execution time) may also be changed by the user during simulation. Depending on the scheduling policy, the change of an attribute may lead to a context switch. E.g., if the absolute deadline is changed and earliest-deadline-first scheduling is simulated.

In accordance with [Bollella *et al.*, 2000] it is possible to associate two interrupt handlers with each task: a deadline overrun handler (triggered if the task misses its deadline) and an execution time overrun handler (triggered if the task executes longer than its worst-case execution time). These handlers can be used to experiment with dynamic compensation schemes, handling missed deadlines or prolonged computations. Overrun handlers are attached to tasks with the commands `ttAttachDLHandler` and `ttAttachWCETHandler`. See the tutorial example in Section **??** for an example on how to use overrun handlers.

Furthermore, to facilitate arbitrary dynamic scheduling mechanisms, it is possible to attach small pieces of code (*hooks*) to each task. These hooks are executed at different stages during the simulation, as shown in Figure 14. Usually the arrival and release of a task job coincide. The exception is when a job is created while previous jobs have yet to finish. In that case, the arrival hook is executed immediately (at the call of `ttCreateJob`) and the release hook is called when the job is subsequently released from the job queue.

The hooks can, e.g., be used to monitor different scheduling schemes and keep track of context switches and deadline overruns. By default, the hooks implement logging, simulation of context switching, and contain code to trigger the worst-case execution time and deadline overrun handlers possibly associated with the different tasks. For the default hook implementation, see `$DIR/kernel/defaulthooks.cpp`.

13.3 The Kernel Function

The functionality of the TrueTime kernel is implemented by the function `runKernel` located in `$DIR/kernel/ttkernel.cpp`. This function manipulates the basic data structures of the kernel, such as the ready queue and the time queue, and is called by the Simulink call-back functions at appropriate times during the simulation. See Section 13.4 for timing implementation details.

It is also from this function that the code functions for tasks and interrupt handlers are called. The kernel keeps track of the current segment and updates

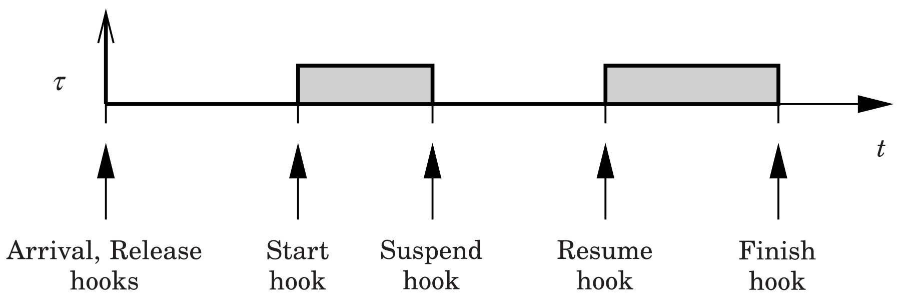


Figure 14 Scheduling hooks.

it when the time associated with the previous segment has elapsed. The hooks mentioned above are also called from this function.

A simple model for how the kernel works is given by the pseudo code in Listing 8. This code focuses on user tasks. See `$DIR/kernel/ttkernel.cpp` for the complete implementation.

13.4 Timing

The TrueTime blocks are event-driven and support external interrupt handling. Therefore, the blocks have a continuous sample time. Discrete (i.e., piecewise constant) outputs are obtained by specifying `FIXED_IN_MINOR_STEP_OFFSET`:

```
static void mdlInitializeSampleTimes(SimStruct *S) {

   ssSetSampleTime(S, 0, CONTINUOUS_SAMPLE_TIME);
   ssSetOffsetTime(S, 0, FIXED_IN_MINOR_STEP_OFFSET);
}
```

The timing of the block is implemented using a zero-crossing function. As we saw above, the next time the kernel should wake up (e.g., because a task is to be released from the time queue or a task has finished its execution) is denoted `nextHit`. If there is no known wake-up time, this variable is set to infinity. The basic structure of the zero-crossing function is

```
static void mdlZeroCrossings(SimStruct *S) {

   Store all inputs;
      if (any interrupt input has changed value) {
         nextHit = ssGetT(S);
      }
   ssGetNonsampledZCs(S)[0] = nextHit - ssGetT(S);
}
```

This will ensure that `mdlOutputs` executes every time an internal or external event has occurred. Since several kernel and network blocks may be connected in a circular fashion, *direct feedthrough* is not allowed. We exploit the fact that, when an input changes as a step, `mdlOutputs` is called, followed by `mdlZeroCrossings`. Since direct feedthrough is not allowed, the inputs may only be checked for changes in `mdlZeroCrossings`. There, the zero-crossing function is changed so that the next major step occurs at the current time. This scheme will introduce a small timing error ($< 10^{-15}$ s).

The kernel function (`runKernel()`) is only called from `mdlOutputs` since this is where the outputs (D/A, schedule, network) can be changed. The timing implementation implies that *zero-crossing detection* must be turned on (this is default, and can be changed under *Simulation Parameters/Advanced*).

14. TrueTime Command Reference

The available TrueTime commands are summarized in Tables 2–4, and the rest of the manual contains detailed descriptions of their functionality. The commands are categorized according to their intended use (**I**; initialization script, **T**; task code function, and **H**; interrupt handler code function). Note that the set and get primitives are collected under the headings `ttSetX` and `ttGetX`, respectively.

By typing `help command`, where `command` is the name of a TrueTime function, in the Matlab command window, the syntax of the various TrueTime functions will be displayed.

Listing 8 Pseudo code for the TrueTime kernel function.

```
double runKernel(void) {

  timeElapsed = rtsys->time - rtsys->prevHit; // time since last invocation
  rtsys->prevHit = rtsys->time;  // update previous invocation time
  nextHit = 0.0;

  while (nextHit == 0.0) {
    // Count down execution time for current task
    // and check if it has finished its execution
    if (there exists a running task) {
      task->execTime -= timeElapsed;
      if (task->execTime == 0.0) {
        task->segment++;
        task->execTime = task->codeFcn(task->segment, task->data);
        if (task->execTime < 0.0) {
          // Negative execution time = task finished
          task->execTime = 0.0;
          task->segment = 0;
          Remove task from readyQ;
          task->finish_hook(task);
          if (job queue is non-empty)
            Release next job and execute release-hook ;
        }
      }
    } // end: counting down execution time of running task

    // Check time queue for possible releases (user tasks or timers)
    for (each task) {
      if ((release time - rtsys->time) == 0.0) {
        Move task to ready queue
      }
    } // end: checking timeQ for releases

    // Determine task with highest priority and make it running task
    newrunning = rtsys->readyQ->getFirst();
    oldrunning = rtsys->running;
    if (oldrunning is being suspended) {
      oldrunning->suspend_hook(oldrunning);
    }
    if (newrunning is being resumed or started) {
      if (newrunning->segment == 0) {
        newrunning->start_hook(newrunning);
      } else {
        newrunning->resume_hook(newrunning);
      }
    } // end: task dispatching

    // Determine next invocation of kernel function
    time1 = remaining execution time of current task;
    time2 = next release time of a task from the time queue
    nextHit = min(time1, time2);
  } // end: loop while nextHit == 0.0
  return nextHit;
}
```

Table 2 Commands used to create and initialize TrueTime objects, and to control the simulation.

Command	Description
`ttInitKernel`	Initialize the kernel, specifying the scheduling policy.
`ttGetInitArg (C++ only)`	Retrieve the init argument from the block dialogue.
`ttCreateTask`	Create an aperiodic task.
`ttCreatePeriodicTask`	Create a periodic task.
`ttCreateLog`	Create a log structure and specify data to log.
`ttCreateHandler`	Create an interrupt handler.
`ttCreateMonitor`	Create a monitor (mutex) for protection of shared data.
`ttCreateEvent`	Create an event (condition variable).
`ttCreateMailbox`	Create a mailbox for inter-task communication.
`ttCreateSempahore`	Create a counting semaphore.
`ttCreateCBS`	Create a soft or hard constant bandwidth server.
`ttNoSchedule`	Switch off the schedule plot for a specific task or interrupt handler.
`ttNonPreemptible`	Make a task non-preemptible.
`ttAttachTriggerHandler`	Attach an interrupt handler to an external trigger.
`ttAttachNetworkHandler`	Attach an aperiodic task or interrupt handler to a network interface.
`ttAttachDLHandler`	Attach a deadline overrun handler to a task.
`ttAttachWCETHandler`	Attach a worst-case execution time overrun interrupt handler to a task.
`ttAttachHook (C++ only)`	Attach a kernel scheduling hook to a task.
`ttAttachCBS`	Attach a task to a constant bandwidth server.
`ttAbortSimulation`	Abort the simulation.

Table 3 Commands used to set and get task or kernel attributes.

Command	Description
`ttSetPeriod`	Set the period of a periodic task.
`ttSetDeadline`	Set the relative deadline of a task.
`ttSetPriority`	Set the priority of a task.
`ttSetWCET`	Set the worst-case execution (maximum budget) time of a task.
`ttSetData`	Update the local memory data structure of a task.
`ttSetAbsDeadline`	Set the absolute deadline of the current job.
`ttSetBudget`	Set the execution time budget of the current job.
`ttSetUserData`	Set arbitrary kernel user data (C++ only).
`ttGetPeriod`	Get the period of a periodic task.
`ttGetDeadline`	Get the relative deadline of a task.
`ttGetPriority`	Get the priority of a task.
`ttGetWCET`	Get the worst-case execution time of a task.
`ttGetData`	Retrieve the local memory data structure of a task.
`ttGetRelease`	Get the release time of the current job.
`ttGetAbsDeadline`	Get the absolute deadline the current job.
`ttGetBudget`	Get the execution-time budget of the current job.
`ttSetUserData`	Set the kernel user data (C++ only).
`ttGetUserData`	Get the kernel user data (C++ only).
`ttSetCBSParameters`	Set the parameters of a constant bandwidth server.

Table 4 Real-time primitives.

Command	Description
`ttCreateJob`	Create a job of a task.
`ttKillJob`	Kill the running (ready) job of a task, if any.
`ttEnterMonitor`	Enter a monitor (blocking).
`ttExitMonitor`	Exit a monitor.
`ttWait`	Wait for an event (blocking).
`ttNotify`	Notify the highest-priority task waiting for an event.
`ttNotifyAll`	Notify all tasks waiting for an event.
`ttLogStart`	Start a timing measurement for a log.
`ttLogStop`	Stop a timing measurement and save in the log.
`ttLogNow`	Log the current time.
`ttLogValue`	Log a scalar value.
`ttTryPost`	Post a message to a mailbox (non-blocking).
`ttTryFetch`	Fetch a message from a mailbox (non-blocking).
`ttPost`	Post a message to a mailbox (blocking).
`ttFetch`	Fetch a message from a mailbox (blocking).
`ttRetrieve`	Read the actual message fetched from a mailbox.
`ttTake`	Take a semaphore.
`ttGive`	Give a semaphore.
`ttCreateTimer`	Create a one-shot timer and associate an interrupt handler with the timer.
`ttCreatePeriodicTimer`	Create a periodic timer and associate an interrupt handler with the timer.
`ttRemoveTimer`	Remove a specific timer.
`ttCurrentTime`	Get and/or set the current time in the simulation on a per node basis.
`ttSleepUntil`	Sleep until a certain point in time.
`ttSleep`	Sleep for a certain amount of time.
`ttAnalogIn`	Read a value from an analog input channel.
`ttAnalogOut`	Write a value to an analog output channel.
`ttSetNextSegment`	Set the next segment to be executed in the code function (to implement loops and branches).
`ttGetInvoker`	Get the name of the external trigger, network interface, or overrun timer that triggered running handler.
`ttCallBlockSystem`	Call a Simulink block diagram from within a code function.
`ttSendMsg`	Send a message over a TrueTime network (non-blocking).
`ttGetMsg`	Get a message that has been received over a TrueTime network (non-blocking).
`ttDiscardUnsentMessages`	Delete any unsent messages.
`ttSetNetworkParameter`	Set a specific network parameter on a per node basis.
`ttSetKernelParameter`	Set a specific kernel parameter on a per node basis.

ttAbortSimulation (TH)

Purpose

Stop the current simulation, raising an error.

Matlab syntax

```
ttAbortSimulation
```

C++ syntax

```
ttAbortSimulation()
```

Description

This function is used to abort a simulation before the simulation stop-time has been reached. For instance, after a certain condition has occurred, it may be pointless to continue the simulation.

If you run repeated simulations in a script, since this primitive generates an error, it may be useful to start the simulation from within a try statement:

```
for i=1:10
  try
    sim('mymodel')
  catch
  end
end
```

ttAnalogIn (TH)

Purpose

Read a value from an analog input channel.

Matlab syntax

```
value = ttAnalogIn(inpChan)
```

C++ syntax

```
double ttAnalogIn(int inpChan)
```

Arguments

`inpChan`	The input channel to read from.

Description

This function is used to read an analog input from the environment. The input channel must be between 1 and the number of analog inputs specified in the kernel block dialogue.

See Also

`ttAnalogOut`

ttAnalogOut (TH)

Purpose

Write a value to an analog output channel. The value is held between updates.

Matlab syntax

```
ttAnalogOut(outpChan, value)
```

C++ syntax

```
void ttAnalogOut(int outpChan, double value)
```

Arguments

`outpChan`	The output channel to write to.
`value`	The value to write.

Description

This function is used to write an analog output to the environment. The output channel must be between 1 and the number of analog outputs specified in the kernel block dialogue.

See Also

`ttAnalogIn`

ttAttachCBS (I)

Purpose

Attach a task to a constant bandwidth server (CBS).

Matlab syntax

```
ttAttachCBS(taskname, CBSname)
```

C++ syntax

```
void ttAttachCBS(char *taskname, char *CBSname)
```

Arguments

`taskname`	The name of the task.
`CBSname`	The name of the constant bandwidth server.

Description

This function is used to associate a task with a constant bandwidth server. Many tasks may be associated with the same CBS. Note the CBSs can only be created under EDF scheduling. A task attached to a CBS inherits the absolute deadline of the CBS when the priority of the task is computed.

See Also

`ttCreateCBS, ttCreateTask, ttCreatePeriodicTask, ttInitKernel`

ttAttachDLHandler (I)

Purpose

Attach a deadline overrun handler to a task.

Matlab syntax

```
ttAttachDLHandler(taskname, handlername)
```

C++ syntax

```
void ttAttachDLHandler(char* taskname, char* handlername)
```

Arguments

`taskname`	Name of a task.
`handlername`	Name of an interrupt handler.

Description

This function is used to attach a deadline overrun handler to a task. The interrupt handler is activated every time the task executes past its absolute deadline.

See Also

`ttCreateHandler`, `ttSetDeadline`, `ttAttachWCETHandler`

ttAttachHook (C++ only) (I)

Purpose

Attach a kernel scheduling hook to a task.

C++ syntax

```
void ttAttachHook(char* taskname, int ID, void (*hook)(UserTask*))
```

Arguments

`taskname`	Name of a task.
`ID`	An identifier for when the hook should be called during simulation. Possible values are `ARRIVAL`, `RELEASE`, `START`, `SUSPEND`, `RESUME`, and `FINISH`.
`hook`	The hook function to be attached.

Description

This function is used to attach a run-time hook to a specific task. The hook identifier determines at which times during the simulation the hook will be called. It is possible to attach hooks that are called when a task job arrives, when the task is released, when the task starts to execute, when the task is suspended, when the task resumes after being suspended, and when the task finishes execution. Usually the arrival and release of a task job coincide. The exception is when a job is created while previous jobs have yet to finish. In that case, the arrival hook is executed immediately (at the call of `ttCreateJob`) but the job is queued. The release hook is called when the job is subsequently released from the job queue.

The input to the hook function is a pointer to a `UserTask` object. `UserTask` inherits from the superclass `Task`. See `$DIR/kernel/usertask.h` and `$DIR/kernel/task.h` for the definitions. The kernel uses hooks internally to implement logging, triggering of task overrun handlers, and simulation of context switching. These hooks are contained in the file `$DIR/kernel/defaulthooks.cpp` and should be included in the user-defined hooks (see the example below).

Example

The example below shows a custom finish hook that estimates the execution time of the task using a first-order filter:

```
void myFinishHook(UserTask* task) {

  // Compute execution time (the initial budget of a task job is the WCET)
  double exectime = task->wcExecTime - task->budget;

  // Update estimate
  double lambda = 0.5;
  task->data->Chat = lambda*task->data->Chat + (1.0-lambda)*exectime;

  // Execute default finish hook
  default_finish(task);
}
```

ttAttachNetworkHandler (I)

Purpose

Attach an aperiodic task or interrupt handler to a network interface.

Matlab syntax

```
ttAttachNetworkHandler(taskname)
ttAttachNetworkHandler(networkNbr, taskname)
```

C++ syntax

```
void ttAttachNetworkHandler(char *taskname)
void ttAttachNetworkHandler(int networkNbr, char *taskname)
```

Arguments

`taskname`	The name of the aperiodic task or interrupt handler that should be invoked when a message arrives over the network.
`networkNbr`	The number of the TrueTime network block. If the TrueTime kernel is only connected to one network, then this argument can be omitted.

Description

This function is used to associate an aperiodic task or interrupt handler with a network interface. The task/handler will be invoked every time a message arrives over the network. If you want to use polling to read network messages, no network handler is needed.

See Also

`ttCreateHandler`

ttAttachTriggerHandler (I)

Purpose

Attach a handler to an external trigger input channel.

Matlab syntax

```
ttAttachTriggerHandler(triggerNbr, handlername)
```

C++ syntax

```
void ttAttachTriggerHandler(int triggerNbr, char *handlername)
```

Arguments

`triggerNbr`	Number of the external trigger interrupt channel.
`handlername`	Name of the interrupt handler to be associated with the external interrupt.

Description

This function is used to associate an interrupt handler with an external trigger channel. The interrupt handler is activated when the signal connected to the trigger port changes value.

See Also

`ttCreateHandler`

ttAttachWCETHandler (I)

Purpose

Attach an execution-time overrun handler to a task.

Matlab syntax

```
ttAttachWCETHandler(taskname, handlername)
```

C++ syntax

```
void ttAttachWCETHandler(char* taskname, char* handlername)
```

Arguments

`taskname`	Name of a task.
`handlername`	Name of an interrupt handler.

Description

This function is used to attach a worst-case execution-time overrun handler to a task. The interrupt handler is activated if the task executes longer than its specified worst-case execution time.

See Also

`ttCreateHandler`, `ttSetWCET`, `ttAttachDLHandler`

ttCallBlockSystem (TH)

Purpose

Call a Simulink block diagram from within a code function.

Matlab syntax

```
outp = ttCallBlockSystem(nbroutp, inp, blockname)
```

C++ syntax

```
void ttCallBlockSystem(int nbroutp, double *outp, int nbrinp,
                       double *inp, char *blockname)
```

Arguments

`nbrinp`	Number of inputs to the block diagram.
`nbroutp`	Number of outputs from the block diagram.
`inp`	Vector of input values.
`outp`	Vector of output values.
`blockname`	The name of the Simulink block diagram.

Description

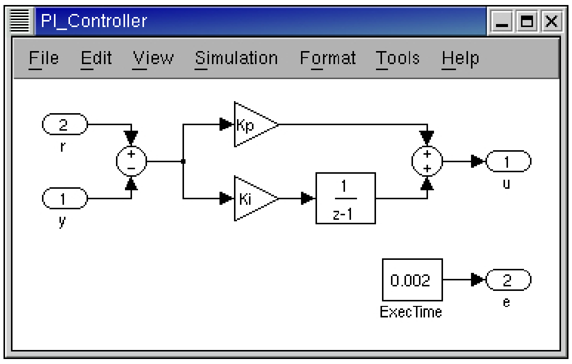
This function is used to call a Simulink block diagram from within a code function. At each call, a one-second simulation of the block is performed, using the old states as initial values. The states of the block diagram are stored internally by the kernel between calls. Consequently, *the block diagrams may only contain discrete blocks and the sampling times should be set to one*. The inputs and outputs are defined by Simulink inports and outports, see the figure below.

Note: Avoid using the "Discrete-Time Integrator" and "Discrete Derivative" Simulink blocks, which seem to implement something else than the transfer functions that are displayed on the blocks. For the "Discrete Derivative" block it is also not possible to specify the sample rate, which makes in incompatible with TrueTime.

Example

Here follows an example using the Simulink diagram in the figure below:

```
function [exectime, data] = PIcontroller(segment, data)

switch segment,
  case 1,
    inp(1) = ttAnalogIn(1);
    inp(2) = ttAnalogIn(2);
    outp = ttCallBlockSystem(2,
           inp, 'PI_Controller');
    data.u = outp(1);
    exectime = outp(2);
  case 2,
    ttAnalogOut(1, data.u);
    exectime = -1;
end
```



ttCreateCBS (I)

Purpose

Create a soft or hard constant bandwidth server (CBS).

Matlab syntax

```
ttCreateCBS(name, Qs, Ts)
ttCreateCBS(name, Qs, Ts, type)
```

C++ syntax

```
void ttCreateCBS(char *name, double Qs, double Ts)
void ttCreateCBS(char *name, double Qs, double Ts, int type)
```

Arguments

`name`	The name of the CBS.
`Qs`	The execution budget per server period.
`Ts`	The server period.

Optional Arguments

`type`	The server type: 0 = Soft CBS (default), 1 = Hard CBS.

Description

This function is used to create a constant bandwidth server (CBS), to be used under EDF scheduling. Any number of tasks may be attached to a CBS. The tasks in the CBS inherit the absolute deadline of the CBS. If the tasks consume more than the execution budget in a server period, the deadline of the CBS is postponed by one period. In the case of Hard CBS, all tasks associated with the CBS are also put to sleep until the next server period.

See Also

`ttAttachCBS`, `ttInitKernel`

Reference

Abeni, L. and Buttazzo, G. (1998): “Integrating multimedia applications in hard real-time systems.” In *Proc. 19th IEEE Real-time Systems Symposium.*

ttCreateEvent (I)

Purpose

Create a TrueTime event (condition variable).

Matlab syntax

```
ttCreateEvent(eventname)
ttCreateEvent(eventname, monitorname)
```

C++ syntax

```
void ttCreateEvent(char *eventname)
void ttCreateEvent(char *eventname, char *monitorname)
```

Arguments

`eventname`	Name of the event. Must be a unique, non-empty string.
`monitorname`	Name of an already created monitor to which the event is to be associated.

Description

This function is used to create an event in the TrueTime kernel. Events may be free, or associated with a monitor.

See Also

`ttWait`, `ttNotify`, `ttNotifyAll`

ttCreateHandler (I)

Purpose

Create a TrueTime interrupt handler.

Matlab syntax

```
ttCreateHandler(name, priority, codeFcn)
ttCreateHandler(name, priority, codeFcn, data)
```

C++ syntax

```
void ttCreateHandler(char *name, double priority,
                              double (*codeFcn)(int, void*))
void ttCreateHandler(char *name, double priority,
                  double (*codeFcn)(int, void*), void* data)
```

Arguments

`name`	Name of the handler. Must be a unique, non-empty string.
`priority`	Priority of the handler. This should be a non-negative value, where a small number represents a high priority.
`codeFcn`	The code function of the handler, where `codeFcn` is a string (name of an m-file) in the Matlab case and a function pointer in the C++ case.
`data`	An arbitrary data structure representing the local memory of the handler.

Description

This function is used to create a handler that will be executed in response to interrupts. Interrupt handlers may be associated with timers, network interfaces, external interrupt channels, or attached to tasks as overrun handlers. A handler may be associated with many interrupt sources.

See Also

`ttCreateTimer`, `ttCreatePeriodicTimer`, `ttAttachTriggerHandler`, `ttAttachNetworkHandler`, `ttAttachDLHandler`, `ttAttachWCETHandler`

ttCreateJob (TH)

Purpose

Create a job of a task.

Matlab syntax

```
ttCreateJob(taskname)
ttCreateJob(taskname, time)
```

C++ syntax

```
void ttCreateJob(char *taskname)
void ttCreateJob(char *taskname, double time)
```

Arguments

`taskname`	Name of a task.
`taskname`	The time at which the job should be created (default=now).

Description

This function is used to create jobs of tasks. If there already is a job active for the task, the job is queued and served as soon as possible. `ttCreateJob` is called to activate aperiodic tasks, i.e., tasks created using `ttCreateTask`. A call to `ttCreateJob` will trigger the arrival hook of the task. If there are no active jobs the release hook will be called as well. Otherwise, the release hook will be called when the job is later activated from the job queue.

See Also

`ttCreateTask`, `ttKillJob`

ttCreateLog (I)

Purpose

Create a user-defined or task-related log.

Matlab syntax

```
ttCreateLog(logname, variable, size)
ttCreateLog(taskname, logtype, variable, size)
```

C++ syntax

```
void ttCreateLog(char* logname, char* variable, int size)
void ttCreateLog(char* taskname, int logtype, char* variable, int size)
```

Arguments

`logname`	The name of the user-defined log. Values can later be written using ttLogStart, ttLogStop, ttLogNow, or ttLogValue.
`variable`	The name of the variable in Matlab workspace to which the log will be written after the simulation.
`size`	The maximum number of elements in the log.
`taskname`	Name of the task for which the log is created.
`logtype`	The task log type (see below).

Description

This function is used to create logs for individual tasks. Five pre-defined log types exist to log response time, release latency, start latency, execution time, and context switch instances. These are obtained by setting the variable `logtype` to any of the constants one to four, respectively. It is also possible to create five additional log structures for each task (by specifying log type number six). These user-controlled logs are written to from the code functions using the primitives `ttLogStart`, `ttLogStop`, `ttLogNow`, and `ttLogValue`. After the simulation the logged attributes can be found in Matlab workspace, having the name specified by `variable`.

The task log types are

1	Response time log
2	Release latency log (time between arrival and release of each job)
3	Start latency log (time between arrival and start of execution for each job)
4	Execution time log

Example

Logging of response time and input-output latency

```
% In initialization script

% Automatic log of response time (type 1)
ttCreateLog('ctrl_task', 1, 'Responsetime', 100);
```

```
% User log #1 (type 6) for logging of I/O latency
ttCreateLog('ctrl_task', 6, 'IOlatency', 100);


% Code function
function [exectime, data] = ctrl(seg, data)

switch seg,
  case 1,
    ttLogStart(1);  % start I/O logging in user log #1
    y = ttAnalogIn(1);   % Input
    data.u = calculateOutput(y);
    exectime = 0.003;
  case 2,
    ttLogStop(1);  % stop and write log entry in user log #1
    ttAnalogOut(1, data.u);  % Output
    exectime = -1;
end
```

See Also

ttLogNow, ttLogStart, ttLogStop

ttCreateMailbox (I)

Purpose

Create a TrueTime mailbox for inter-task communication.

Matlab syntax

```
ttCreateMailbox(mailboxname)
ttCreateMailbox(mailboxname, maxsize)
```

C++ syntax

```
void ttCreateMailbox(char *mailboxname)
void ttCreateMailbox(char *mailboxname, int maxsize)
```

Arguments

`mailboxname`	Name of the mailbox. Must be a unique, non-empty string.
`maxsize`	The size of the buffer associated with the mailbox (default is INT_MAX)

Description

This function is used to create a mailbox for communication between tasks. The TrueTime mailbox implements asynchronous message passing with indirect naming. A buffer is used to store incoming messages, and the maximum size of this buffer may be specified by `maxsize`.

See Also

`ttTryPost`, `ttTryFetch`, `ttPost`, `ttFetch`, `ttRetrieve`

ttCreateMonitor (I)

Purpose

Create a TrueTime monitor.

Matlab syntax

```
ttCreateMonitor(name, display)
```

C++ syntax

```
void ttCreateMonitor(char *name, bool display)
```

Arguments

`name`	Name of the monitor. Must be a unique, non-empty string.
`display`	To indicate if the monitor should be included in the monitor graph generated by the simulation.

Description

This function is used to create a monitor for task synchronization. Condition variables for the monitor can be created using `ttCreateEvent`. The kernel block has a monitor output that will display a graph showing when the various tasks have access to the monitors.

See Also

`ttEnterMonitor`, `ttExitMonitor`, `ttCreateEvent`, `ttWait`, `ttNotify`, `ttNotifyAll`

ttCreatePeriodicTask (I)

Purpose

Create a periodic TrueTime task.

Matlab syntax

```
ttCreatePeriodicTask(name, starttime, period, codeFcn)
ttCreatePeriodicTask(name, starttime, period, codeFcn, data)
```

C++ syntax

```
void ttCreatePeriodicTask(char* name, double starttime, double period,
       double (*codeFcn)(int, void*))
void ttCreatePeriodicTask(char* name, double starttime, double period,
       double (*codeFcn)(int, void*), void* data)
```

Arguments

`name`	Name of the task. Must be a unique, non-empty string.
`starttime`	Release time for the first job of the periodic task.
`period`	Period of the task.
`codeFcn`	The code function of the task, where `codeFcn` is a string (name of an m-file) in the Matlab case and a function pointer in the C++ case.
`data`	An arbitrary data structure representing the local memory of the task.

Description

This function is used to create a periodic task to run in the TrueTime kernel. The periodicity is implemented internally by the kernel using a periodic timer. See the simple PID-control example in `$DIR/examples/simple` for other ways to implement periodic activities. *The deadline and worst-case execution time of the task are by default set equal to the task period*. This may be changed by a suitable set-function.

See Also

`ttCreateTask`, `ttSetX`

ttCreatePeriodicTimer (ITH)

Purpose

Create a periodic timer and associate an interrupt handler with the timer.

Matlab syntax

```
ttCreatePeriodicTimer(timername, period, handlername)
ttCreatePeriodicTimer(timername, offset, period, handlername)
```

C++ syntax

```
void ttCreatePeriodicTimer(char *timername, double period, char *handlername)
void ttCreatePeriodicTimer(char *timername, double offset, double period,
                           char *handlername)
```

Arguments

`timername`	Name of the timer. Must be unique, non-empty string.
`offset`	The time for the first expiry of the timer (default = 0).
`period`	The period of the timer.
`handlername`	Name of interrupt handler associated with the timer.

Description

This function is used to create a periodic timer. Each time the timer expires the associated interrupt handler is activated and scheduled for execution.

See Also

`ttCreateInterruptHandler`, `ttCreateTimer`, `ttRemoveTimer`

ttCreateSemaphore (I)

Purpose

Create a simple, counting TrueTime semaphore.

Matlab syntax

```
ttCreateSemaphore(name, initval)
ttCreateSemaphore(name, initval, maxval)
```

C++ syntax

```
void ttCreateSemaphore(char *name, int initval)
void ttCreateSemaphore(char *name, int initval, int maxval)
```

Arguments

`name`	Name of the semaphore. Must be a unique, non-empty string.
`initval`	The initial value of the semaphore. Must be an integer.
`maxval`	The maximum value of the semaphore. Must be an integer. The default maximum value is INT_MAX.

Description

This function is used to create a simple, counting semaphore. Semaphores can be used to synchronize tasks, for instance, to synchronize a producer and a consumer task. Note that a semaphore does not have the concept of a current owner task and hence should not be used to achieve mutual exclusion.

The `ttGive` command has no effect if the current value of the semaphore is equal to `maxval`. To create a binary semaphore, set `maxval` to 1.

Compared to TrueTime monitors, TrueTime sempahores do not produce any output graphs. Also, they do not support any priority inheritance protocol, but rather implement a simple FIFO waiting queue.

DO NOT use semaphores to protect critical regions! For that purpose you should use monitors!

See Also

`ttTake`, `ttGive`

ttCreateTask (I)

Purpose

Create an aperiodic TrueTime task.

Matlab syntax

```
ttCreateTask(name, deadline, codeFcn)
ttCreateTask(name, deadline, codeFcn, data)
```

C++ syntax

```
void ttCreateTask(char* name, double deadline,
                  double (*codeFcn)(int, void*))
void ttCreateTask(char *name, double deadline,
                  double (*codeFcn)(int, void*), void* data)
```

Arguments

`name`	Name of the task. Must be a unique, non-empty string.
`deadline`	Relative deadline of the task.
`codeFcn`	The code function of the task, where `codeFcn` is a string (name of an m-file) in the Matlab case and a function pointer in the C++ case.
`data`	An arbitrary data structure representing the local memory of the task.

Description

This function is used to create a task to run in the TrueTime kernel. *The worst-case execution time of the task is by default set equal to the task deadline*. This may be changed by a suitable set-function.

See Also

`ttCreatePeriodicTask`, `ttCreateJob`, `ttSetX`

ttCreateTimer (ITH)

Purpose

Create a one-shot timer and associate an interrupt handler with the timer.

Matlab syntax

```
ttCreateTimer(timername, time, handlername)
```

C++ syntax

```
void ttCreateTimer(char *timername, double time, char *handlername)
```

Arguments

`timername`	Name of the timer. Must be unique, non-empty string.
`time`	The time when the timer is set to expire.
`handlername`	Name of interrupt handler associated with the timer.

Description

This function is used to create a one-shot timer. When the timer expires the associated interrupt handler is activated and scheduled for execution.

See Also

`ttCreateInterruptHandler`, `ttCreatePeriodicTimer`, `ttRemoveTimer`

ttCurrentTime (ITH)

Purpose

Get and/or set the current time in the simulation on a per node basis.

Matlab syntax

```
time = ttCurrentTime
time = ttCurrentTime(newTime)
```

C++ syntax

```
double ttCurrentTime()
double ttCurrentTime(double newTime)
```

Arguments

`newTime`	Sets the current time to this time.

Description

This function returns the current time in the simulation, in seconds. When the function is used to set the current time, the old current time is returned.

ttDiscardUnsentMessages (IT)

Purpose

Delete unsent messages in the network queue.

Matlab syntax

```
nbr = ttDiscardUnsentMessages
nbr = ttDiscardUnsentMessages(network)
```

C++ syntax

```
int ttDiscardUnsentMessages()
int ttDiscardUnsentMessages(int network)
```

Arguments

`network`	The network interface from which messages should be deleted (default is 1).

Description

This function can be used to delete any unsent messages waiting in the network interface output queue. A message that has already started to be sent is not affected. The function returns the total number of deleted messages.

ttEnterMonitor (T)

Purpose

Enter a monitor, blocking if the monitor is not free.

Matlab syntax

```
ttEnterMonitor(monitorname)
```

C++ syntax

```
void ttEnterMonitor(char *monitorname)
```

Arguments

`monitorname`	Name of a monitor.

Description

This function is used to attempt to enter a monitor. If the attempt fails, the task will be removed from the ready queue and inserted in the waiting queue of the monitor (the waiting queue is sorted using the priority function in the same way as the ready queue). This will also trigger the suspend hook of the task.

When the task currently holding the monitor exits, the first task in the waiting queue will be moved to the ready queue and is now holding the monitor. Execution will then resume in the segment after the call to `ttEnterMonitor`. To ensure that no further instructions are executed in the case that `ttEnterMonitor` fails, it needs to be called from its own segment (since all code of a TrueTime segment is executed at once before scheduling decisions are made). See the example below.

To avoid *priority inversion*, standard *priority inheritance* is used if a task tries to enter a monitor currently held by a lower priority task.

Example

```
function [exectime, data] = ctrl(seg, data)
switch seg,
  case 1,
    ttEnterMonitor('mutex');
    exectime = 0;
  case 2,
    if some_condition_not_fulfilled
      ttWait('condvar');
      ttSetNextSegment(2);
      exectime = 0;
    else
      criticalOperation;
      exectime = 0.005;
    end
  case 3,
    ttExitMonitor('mutex');
    exectime = -1;
end
```

See Also

`ttCreateMonitor`, `ttExitMonitor`, `ttCreateEvent`, `ttWait`, `ttNotify`, `ttNotifyAll`

ttExitMonitor (T)

Purpose

Exit a monitor.

Matlab syntax

```
ttExitMonitor(monitorname)
```

C++ syntax

```
void ttExitMonitor(char *monitorname)
```

Arguments

`monitorname`	Name of a monitor.

Description

This function is used to exit a monitor. The function can only be called by the task currently holding the monitor. The call will cause the first task in the waiting queue of the monitor to be moved to the ready queue. To ensure that no further instructions are executed in the case that a context switch should occur when the monitor is released, `ttExitMonitor` needs to be called from its own segment (since all code of a TrueTime segment is executed at once before scheduling decisions are made).

Example

See `ttEnterMonitor`.

See Also

`ttCreateMonitor`, `ttEnterMonitor`

ttFetch (T)

Purpose

Fetch a message from a mailbox, blocking if the mailbox is empty.

Matlab syntax

```
ttFetch(mailboxname)
```

C++ syntax

```
void ttFetch(char *mailboxname)
```

Arguments

`mailboxname`	Name of a mailbox.

Description

This function is used to wait for a message at a mailbox. If the mailbox is empty, the task will be blocked until a message has arrived. Tasks waiting to fetch from a mailbox are sorted in FIFO order.

Note that this function does not read the actual message – that is done using `ttRetrieve`. (This somewhat akward solution is due to the segment structure of TrueTime.)

Example

```
function [exectime, data] = ctrl(seg, data)
switch seg,
  case 1,
    ttFetch('mailbox');            % wait for a message
    exectime = 0;
  case 2,
    msg = ttRetrieve('mailbox');   % read the actual message
    doStuff;
    exectime = 0.005;
  case 3,
    exectime = -1;
end
```

See Also

`ttCreateMailbox`, `ttTryPost`, `ttTryFetch`, `ttPost`, `ttRetrieve`

ttGetData (TH)

Purpose

Retrieve the local memory data structure associated with a specific task.

Matlab syntax

```
data = ttGetData(taskname)
```

C++ syntax

```
void *ttGetData(char *taskname)
```

Arguments

`taskname`	Name of a task.

Description

This function is used to retrieve the data structure of a specific task. The data structure represents local memory of the task and is normally updated in the code function of the task. Using this function in combination with `ttSetData` it is possible to modify the data also outside the code function.

See Also

`ttSetData, ttCreateTask, ttCreatePeriodicTask`

ttGetMsg (TH)

Purpose

Get a message that has been received over a network. This function is used both for wired and wireless networks.

Matlab syntax

```
[msg, signalPower] = ttGetMsg
[msg, signalPower] = ttGetMsg(network)
```

C++ syntax

```
void *ttGetMsg()
void *ttGetMsg(int network)
void *ttGetMsg(int network, double *signalPower)
```

Arguments

`network`	The network interface from which the message should be received. The default network number is 1.
`signalPower`	The value of the received signal power corresponding to this message. Only used in the wireless network.

Description

This function is used to retrieve a message that has been received over the network. Typically, you have been notified that a message exists in the network interface input queue by an interrupt, but it is also possible to poll for new messages. If no message exists, the function will return NULL (C++) or an empty matrix (Matlab).

Example

```
% Task that waits for and reads messages
function [exectime, data] = receiver(seg, data)
switch seg,
  case 1,
    ttWait('message');
    exectime = 0;
  case 2,
    msg = ttGetMsg;
    disp('I got a message!');
    exectime = 0.001;
  case 3,
    ttSetNextSegment(1); % loop back and wait for new message
    exectime = 0;
end
% Interrupt handler that is called by the network interface
function [exectime, data] = msgRcvhandler(seg, data)
ttNotifyAll('message');
exectime = -1;
```

See Also

`ttAttachNetworkHandler`, `ttSendMsg`

ttGetInitArg (C++ only) (I)

Purpose

Retrieve a pointer to the init argument of the TrueTime block.

C++ syntax

```
mxArray *ttGetInitArg()
```

ttGetInvoker (H)

Purpose

Get the name of the interrupt source that invoked a handler.

Matlab syntax

```
invoker = ttGetInvoker
```

C++ syntax

```
char *ttGetInvoker()
```

Description

This function returns the name of the external trigger, network interface, or overrun timer that triggered running handler.

ttGetX (ITH)

Purpose

Get a specific task attribute.

Matlab syntax

```
value = ttGetX
value = ttGetX(taskname)
```

C++ syntax

```
double ttGetX()
double ttGetX(char *taskname)
```

Arguments

`taskname`	Name of a task.

Description

These functions are used to retrieve values of task attributes. There exist functions for the following attributes (with the true function name in parenthesis):

- arrival time (`ttGetArrival`)
- release time (`ttGetRelease`)
- relative deadline (`ttGetDeadline`)
- absolute deadline (`ttGetAbsDeadline`)
- priority (`ttGetPriority`)
- period (`ttGetPeriod`)
- worst-case execution time (`ttGetWCET`)
- execution time budget (`ttGetBudget`)

Use the `ttGetX` functions to retrieve the current attributes of a task. All the functions exist in overloaded versions as shown by the syntax above. If the argument `taskname` is not specified, the call will affect the currently running task. Below follow some special notes on the individual functions:

ttGetArrival: Returns the time when the current task job was created. An error will occur if the task has no running job.

ttGetRelease: Returns the time when the current task job was released. An error will occur if the task has no running job.

ttGetDeadline: Returns the relative deadline of the task.

ttGetAbsDeadline: Returns the absolute deadline of the current task job. An error will occur if the task has no running job.

ttGetPriority: Returns the assigned base priority of the task.

ttGetPeriod: Returns the period of a periodic task. An error will occur if the task is not periodic.

ttGetWCET: Returns the worst-case execution time of a task.

ttGetBudget: Returns the remaining execution time budget of the current task job. The execution time budget is decreased each time a new segment of the code function is executed, as well as when the task is suspended by another task. The execution time budget is reset to the worst-case execution time at the start of each task job.

See Also

`ttSetX`

ttGive (TH)

Purpose

Give (signal) a semaphore.

Matlab syntax

```
ttGive(semname)
```

C++ syntax

```
void ttGive(char *semname)
```

Arguments

`semname`	The name of the semaphore.

Description

This function is used to signal a semaphore. Its semantics can be described by the following pseudo-code:

```
if (value < maxval) {
  value++;
  if (value <= 0) {
    release the first task from the semaphore queue;
  }
}
```

See Also

`ttCreateSemaphore`, `ttTake`

ttInitKernel (I)

Purpose

Initialize the TrueTime kernel.

Matlab syntax

```
ttInitKernel(prioFcn)
ttInitKernel(prioFcn, contextSwitchOverhead)
```

C++ syntax

```
void ttInitKernel(double (*prioFcn)(UserTask*))
void ttInitKernel(double (*prioFcn)(UserTask*), double contextSwitchOverhead)
```

Arguments

`prioFcn`	The scheduling policy used by the kernel.
`contextSwitchOverhead`	The overhead time for a context switch. Optional argument, taken as zero if not specified.

Description

This function performs necessary initializations of the kernel block and *must* be called first of all in the initialization script. The priority function should be one of the following in the Matlab case: `'prioFP'` (fixed-priority scheduling), `'prioDM'` (deadline-monotonic scheduling), or `'prioEDF'` (earliest-deadline-first scheduling, with support for constant bandwidth servers). A task associated with a CBS is scheduled according to the deadline of the CBS and not of the task.

In the C++ case, an arbitrary priority function can be supplied. There are pre-defined priority functions called `prioFP`, `prioDM`, and `prioEDF`.

The schedule plot for the context switches can be turned off by a call to `ttNoSchedule('CShandler')`.

Example

The pre-defined priority functions for deadline-monotonic scheduling and earliest-deadline-first scheduling are given below. Note that a small return value corresponds to a high priority.

```
/* Priority function for deadline-monotonic scheduling */
double prioDM(UserTask* t) {
  return t->deadline;
}

/* Priority function for earliest-deadline-first scheduling,
   with support for constant bandwidth servers */
double prioEDF(UserTask* t) {
  if (t->cbs) {
    // The task is associated with a CBS: inherit the deadline of the CBS
    return t->cbs->ds;
  } else {
    // No CBS: return the absolute deadline of the task
    return t->absDeadline;
  }
}
```

ttKillJob (TH)

Purpose

Kill the current job of a task.

Matlab syntax

```
ttKillJob(taskname)
```

C++ syntax

```
void ttKillJob(char *taskname)
```

Arguments

`taskname`	Name of a task.

Description

This function is used to kill the current active job of a task. The finish hook of the task will be called as the job is killed. If there exist pending jobs for the task that should be released, the first job in the queue will be scheduled for execution and the release hook will be called.

See Also

`ttCreateJob`

ttLogNow (TH)

Purpose

Log the current time in a user-controlled log.

Matlab syntax

```
ttLogNow(logname)
```

C++ syntax

```
void ttLogNow(char *logname)
```

Arguments

`logID`	The identifier of the user-controlled log.

Description

This function is used to write the current time in user-controlled logs, i.e., logs that have been created using `ttCreateLog` and `logtype = 6`. `logID` should be a number between one and five that identifies which log to write to. The logs are numbered in order of creation.

See Also

`ttCreateLog`, `ttLogStart`, `ttLogStop`

ttLogStart (TH)

Purpose

Start a timing measurement in a user-controlled log.

Matlab syntax

```
ttLogStart(logID)
```

C++ syntax

```
void ttLogStart(int logID)
```

Arguments

`logID`	The identifier of the user-controlled log.

Description

This function is used to start timing measurements in user-controlled logs, i.e., logs that have been created using `ttCreateLog` and `logtype = 6`. `logID` should be a number between and one and five that identifies which log to write to. The logs are numbered in order of creation. Note that nothing is written in the log until a subsequent call to `ttLogStop`.

Example

See the example in the description of `ttCreateLog` that shows how to use `ttLog-Start` and `ttLogStop` to log input-output latency in a code function.

See Also

`ttCreateLog`, `ttLogStop`, `ttLogNow`

ttLogStop (TH)

Purpose

Stop a timing measurement in a user-controlled log.

Matlab syntax

`ttLogStop(logID)`

C++ syntax

`void ttLogStop(int logID)`

Arguments

`logID`	The identifier of the user-controlled log.

Description

This function is used to stop timing measurements in user-controlled logs, i.e., logs that have been created using `ttCreateLog` and `logtype = 6`. `logID` should be a number between and one and five that identifies which log to write to. The logs are numbered in order of creation. When this function is called, the difference between the current time and the time of the associated `ttLogStart` will be written in the log.

Example

See the example in the description of `ttCreateLog` that shows how to use `ttLogStart` and `ttLogStop` to log input-output latency in a code function.

See Also

`ttCreateLog`, `ttLogStart`, `ttLogNow`

ttLogValue (TH)

Purpose

Log a scalar value in a user-controlled log.

Matlab syntax

```
ttLogValue(logname, value)
```

C++ syntax

```
void ttLogValue(char *logname, double value)
```

Arguments

`logname`	The identifier of the user-controlled log.
`value`	The scalar value to log.

Description

This function is used to write the current time in user-controlled logs, i.e., logs that have been created using `ttCreateLog` and `logtype = 6`. `logID` should be a number between one and five that identifies which log to write to. The logs are numbered in order of creation.

See Also

`ttCreateLog`, `ttLogStart`, `ttLogStop`

ttNonPreemptible (I)

Purpose

Make a user task or handler non-preemptible.

Matlab syntax

```
ttNonPreemptible(taskname)
```

C++ syntax

```
void ttNonPreemptible(char* taskname)
```

Arguments

`taskname`	Name of a task.

Description

Tasks are by default preemptible. Use this function to specify that a task can not be preempted by other tasks. Non-preemptible tasks may, however, still be preempted by interrupts.

ttNoSchedule (I)

Purpose

Switch off the schedule plot for a specific task or interrupt handler.

Matlab syntax

```
ttNoSchedule(name)
```

C++ syntax

```
void ttNoSchedule(char* name)
```

Arguments

`name`	Name of a task or interrupt handler.

Description

This function is used to switch off the schedule plot for a specific task or interrupt handler. The schedule output is generated by default and this function must be called to turn it off. This function can only be called from the initialization script.

The schedule plot for the context switches can be turned off by specifying the name `'CShandler'`.

ttNotify (TH)

Purpose

Notify the highest-priority task waiting for an event.

Matlab syntax

```
ttNotify(eventname)
```

C++ syntax

```
void ttNotify(char *eventname)
```

Arguments

`eventname`	Name of an event.

Description

This function is used to notify the first task in the waiting queue associated with an event. The waiting queue is sorted according to the priority function of the kernel (in the same way as the ready queue). If the event is associated with a monitor, `ttNotify` must be performed inside a `ttEnterMonitor-ttExitMonitor` construct. The highest-priority waiting task will be moved to the waiting queue of the associated monitor, or directly to the ready queue if it is a free event.

See Also

`ttCreateEvent`, `ttWait`, `ttNotifyAll`

ttNotifyAll (TH)

Purpose

Notify all tasks waiting for an event.

Matlab syntax

```
ttNotifyAll(eventname)
```

C++ syntax

```
void ttNotifyAll(char *eventname)
```

Arguments

`eventname`	Name of an event.

Description

This function is used to notify all tasks waiting for an event. If the event is associated with a monitor, `ttNotifyAll` must be performed inside a `ttEnterMonitor`-`ttExitMonitor` construct. The call will cause all tasks waiting for the event to be moved to the waiting queue of the associated monitor, or directly to the ready queue if it is a free event.

See Also

`ttCreateEvent`, `ttWait`, `ttNotify`

ttPost (T)

Purpose

Post a message to a mailbox, blocking if the mailbox is full.

Matlab syntax

```
ttPost(mailboxname, msg)
```

C++ syntax

```
void ttPost(char *mailboxname, void* msg)
```

Arguments

`mailboxname`	Name of a mailbox.
`msg`	An arbitrary data structure representing the contents of the message to be posted.

Description

This function is used to post messages to a mailbox. If the mailbox is full, the task will be blocked. Tasks waiting to post to a mailbox are sorted in FIFO order.

See Also

`ttCreateMailbox`, `ttTryPost`, `ttTryFetch`, `ttFetch`, `ttRetrieve`

ttRemoveTimer (TH)

Purpose

Remove a specific timer.

Matlab syntax

```
ttRemoveTimer(timername)
```

C++ syntax

```
void ttRemoveTimer(char *timername)
```

Arguments

`timername`	Name of the timer to be removed.

Description

This function is used to remove timers. Both one-shot and periodic timers can be removed by this function. Using this function on a periodic timer will remove the timer completely, and not only the current job.

See Also

`ttCreateTimer`, `ttCreatePeriodicTimer`

ttRetrieve (T)

Purpose

Read a message that was fetched using `ttFetch`.

Matlab syntax

```
msg = ttRetrieve(mailboxname)
```

C++ syntax

```
void* ttRetrieve(char *mailboxname)
```

Arguments

`mailboxname`	Name of a mailbox.

Description

This function may only be called if `ttFetch` was called in the previous segment. It is used to read the fetched message. (This somewhat akward solution is due to the fact that blocking primitives in TrueTime cannot return any data.)

Example

```
function [exectime, data] = ctrl(seg, data)
switch seg,
  case 1,
    ttFetch('mailbox');            % wait for a message
    exectime = 0;
  case 2,
    msg = ttRetrieve('mailbox');   % read the actual message
    doStuff;
    exectime = 0.005;
  case 3,
    exectime = -1;
end
```

See Also

`ttTryPost`, `ttTryFetch`, `ttPost`, `ttFetch`

ttSendMsg (TH)

Purpose

Send a message over a network.

Matlab syntax

```
ttSendMsg(receiver, data, length)
ttSendMsg(receiver, data, length, priority)
ttSendMsg([network receiver], data, length)
ttSendMsg([network receiver], data, length, priority)
```

C++ syntax

```
void ttSendMsg(int receiver, void *data, int length)
void ttSendMsg(int receiver, void *data, int length, int priority)
void ttSendMsg(int network, int receiver, void *data, int length)
void ttSendMsg(int network, int receiver, void *data, int length, int priority)
```

Arguments

`network`	The network interface on which the message should be sent. The default network number is 1.
`receiver`	The number of the receiving node (a number between 1 and the number of nodes). It is allowed to send messages to oneself. Specify receiver number 0 to broadcast a message to all nodes in the network.
`data`	An arbitrary data structure representing the contents of the message.
`length`	The length of the message, in bits. Determines the time it will take to transmit the message.
`priority`	The priority of the message (relevant only for CSMA/AMP networks). If not specified, the priority will be given by the number of the sending node, i.e., messages sent from node 1 will have the highest priority by default.

See Also

`ttGetMsg`

ttSetCBSParameters (ITH)

Purpose

Change the parameters of a constant bandwidth server (CBS).

Matlab syntax

```
ttSetCBSParameters(cbsname, Qs, Ts)
```

C++ syntax

```
void ttSetCBSParameters(char *cbsname, double Qs, double Ts)
```

Arguments

`cbsname`	Name of a CBS.
`Qs`	Server budget.
`Ts`	Server period.

Description

See Also

`ttCreateCBS`

ttSetData (TH)

Purpose

Update the local memory data structure associated with a specific task.

Matlab syntax

```
ttSetData(taskname, data)
```

Arguments

`taskname`	Name of a task.
`data`	Updated data structure.

Description

This function is used to update the data structure of a specific task. The data structure represents local memory of the task and is normally updated in the code function of the task. Using this function in combination with `ttGetData` it is possible to modify the data also outside the code function.

The `ttSetData` function only exists in Matlab syntax. No C++ version is needed, since `ttGetData` gives a pointer to the task data structure.

See Also

`ttGetData`, `ttCreateTask`, `ttCreatePeriodicTask`

ttSetKernelParameter (ITH)

Purpose

Set a specific kernel parameter.

Matlab syntax

```
ttSetKernelParameter(parameter, value)
```

C++ syntax

```
void ttSetKernelParameter(char* parameter, double value)
```

Arguments

`parameter`	The name of the parameter to be changed.
`value`	The new value of the parameter.

Description

This function makes it possible to change kernel parameters on the fly. At the moment the following parameters are supported:

- `cpuscaling`
- `energyconsumption`

The default parameter value is 1 for `cpuscaling`, and 0 for `energyconsumption`. Setting the cpuscaling to 2 will make the kernel block execute everything twice as fast as with 1. This makes it possible to experiment with different Dynamic Voltage Scaling methods. At the same time the energy consumption can be set to a realistic value and connected to a battery block.

ttSetNetworkParameter (ITH)

Purpose

Set a specific network parameter on a per node basis.

Matlab syntax

```
ttSetNetworkParameter(parameter, value)
ttSetNetworkParameter(networkNbr, parameter, value)
```

C++ syntax

```
void ttSetNetworkParameter(char* parameter, double value)
void ttSetNetworkParameter(int networkNbr, char* parameter, double value)
```

Arguments

`parameter`	The name of the parameter to be changed.
`value`	The new value of the parameter.
`networkNbr`	The network interface on which the parameter should be changed. The default network number is 1.

Description

This function makes it possible to change network parameters on a per node basis. At the moment the following parameters are supported:

`'transmitpower'` The transmitpower parameter is only valid when using the wireless network and defaults to whatever is set in the block mask.

`'predelay'` The time a message is delayed by the network interface on the sending end. This can be used to model, e.g., a slow serial connection between the computer and the network interface. The default value is zero.

`'postdelay'` The time a message is delayed by the network interface on the receiving end. The default value is zero.

ttSetNextSegment (TH)

Purpose

Set the next segment to be executed in the code function.

Matlab syntax

```
ttSetNextSegment(segment)
```

C++ syntax

```
void ttSetNextSegment(int segment)
```

Arguments

`segment`	Number of the segment.

Description

This function is used to set the next segment to be executed, overriding the normal execution order. This can be used to implement conditional branching and loops (see, e.g., the description of `ttWait`). The segment number should be between 1 and the number of segments defined in the code function.

ttSetX (ITH)

Purpose

Set a specific task attribute.

Matlab syntax

```
ttSetX(value)
ttSetX(value, taskname)
```

C++ syntax

```
void ttSetX(double value)
void ttSetX(double value, char *taskname)
```

Arguments

`value`	Value to be set.
`taskname`	Name of a task.

Description

These functions are used to manipulate task attributes. There exist functions for the following attributes (with the true function name in parenthesis):

- relative deadline (`ttSetDeadline`)
- absolute deadline (`ttSetAbsDeadline`)
- priority (`ttSetPriority`)
- period (`ttSetPeriod`)
- worst-case execution time (`ttSetWCET`)
- execution time budget (`ttSetBudget`)

Use the `ttSetX` functions to change the default attributes defined by `ttCreateTask` and `ttCreatePeriodicTask`. All these functions exist in overloaded versions as shown by the syntax above. If the argument `taskname` is not specified, the call will affect the currently running task. Below follow some special notes on the individual functions:

ttSetDeadline: Changing the relative deadline of a task will only affect subsequent task jobs and not the absolute deadline of the currently running task job. If deadline-monotonic scheduling is used, a call to this function may lead to a context switch, or a re-ordering of the ready queue.

ttSetAbsDeadline: A call to this function will only affect the absolute deadline for the current task job. If a deadline overrun handler is attached to the task, this will be triggered based on the new absolute deadline. Using earliest-deadline-first scheduling, a call to this function may cause a context switch, or a re-ordering of the ready queue. An error will occur if the task has no running job.

ttSetPriority: Priority values for tasks should be non-negative. In the case of fixed-priority scheduling a call to this function may lead to a context switch, or a re-ordering of the ready queue.

ttSetPeriod: This function is only applicable to periodic tasks. Assuming a period h_1 before the call, task jobs are created at times h_1, $2h_1$, $3h_1$, etc. If the call is executed at time $h_1 + \tau$, new task jobs will be created at the times $h_1 + h_2$, $h_1 + 2h_2$, $h_1 + 3h_2$, etc., where h_2 is the new period of the task. Using rate-monotonic scheduling, a call to this function may cause a context switch, or a re-ordering of the ready queue. An error will occur if the task is not periodic.

ttSetWCET: Changes the worst-case execution time of the task. Each new task job will get an execution time budget equal to the worst-case execution time associated with task. A call to this function will not influence the execution time budget of the currently running task job.

ttSetBudget: This call is used to dynamically change the execution time budget of a running task job. When a task job is created, the execution time budget is set to the worst-case execution time of the task. A call to this function will only have effect if there is a worst-case execution time overrun handler attached to the task. This handler is activated when the budget is exhausted, and will be triggered based on the new execution time budget.

See Also

`ttCreateTask`, `ttCreatePeriodicTask`, `ttGetX`

ttSleep (T)

Purpose

Put the running task to sleep for a certain time.

Matlab syntax

```
ttSleep(duration)
```

C++ syntax

```
void ttSleep(double duration)
```

Arguments

`duration`	The time that the task should sleep.

Description

This function is used to make the running task sleep for a specified amount of time. This function is equivalent to `ttSleepUntil(duration + ttCurrentTime())`. A call to this function will trigger execution of the suspend-hook of the task. When the task wakes up, the resume-hook will be executed.

See Also

`ttSleepUntil`

ttSleepUntil (T)

Purpose

Put the running task to sleep until a certain point in time.

Matlab syntax

```
ttSleepUntil(time)
```

C++ syntax

```
void ttSleepUntil(double time)
```

Arguments

`time`	The time when the task should wake up.

Description

This function is used to make the running task sleep until a specified point in time. A call to this function will trigger execution of the suspend-hook of the task.

See Also

`ttSleep`

ttTake (T)

Purpose

Take (wait for) a semaphore, blocking if the counter is zero or below.

Matlab syntax

```
ttTake(semname)
```

C++ syntax

```
void ttTake(char *semname)
```

Arguments

`semname`	The name of the semaphore.

Description

This function is used to take a semaphore. Its semantics can be described by the following pseudo-code:

```
value--;
if (value < 0) {
  suspend the task and put it in the semaphore queue;
}
```

Example

```
function [exectime, data] = producer_code(seg, data)
switch seg,
  case 1,
    produce_data;
    exectime = 0.020;
  case 2,
    ttTake('sem'); % wait until the consumer task is ready
    exectime = 0;
  case 3,
    send_data_to_consumer;
    exectime = 0.005;
  case 4,
    exectime = -1;
end
```

See Also

`ttCreateSemaphore`, `ttGive`

ttTryFetch (TH)

Purpose

Fetch a message from a mailbox (non-blocking).

Matlab syntax

```
msg = ttTryFetch(mailboxname)
```

C++ syntax

```
void* ttTryFetch(char* mailboxname)
```

Arguments

`mailboxname`	Name of a mailbox.

Description

This function is used to fetch messages from a mailbox. If successful, the function returns the oldest message in the buffer of the mailbox. Otherwise, it returns NULL (C++) or an empty matrix (Matlab).

See Also

`ttCreateMailbox`, `ttTryPost`, `ttPost`, `ttFetch`, `ttRetrieve`

ttTryPost (TH)

Purpose

Post a message to a mailbox (non-blocking).

Matlab syntax

```
ok = ttTryPost(mailboxname, msg)
```

C++ syntax

```
bool ttTryPost(char* mailboxname, void* msg)
```

Arguments

`mailboxname`	Name of a mailbox.
`msg`	An arbitrary data structure representing the contents of the message to be posted.

Description

This function is used to post messages to a mailbox. If successful, the message is put in the buffer of the mailbox, and the function returns `true`. Otherwise, the function returns `false`.

See Also

`ttCreateMailbox`, `ttTryFetch`, `ttPost`, `ttFetch`, `ttRetrieve`

ttWait (T)

Purpose

Wait for an event (blocking).

Matlab syntax

```
ttWait(eventname)
```

C++ syntax

```
void ttWait(char *eventname)
```

Arguments

`eventname`	Name of an event.

Description

This function is used to wait for an event. If the event is associated with a monitor, the call must be performed inside a `ttEnterMonitor-ttExitMonitor` construct. The call will cause the task to be moved from the ready queue to the waiting queue of the event (the waiting queue is sorted using the priority function in the same way as the ready queue). When the task is later notified, it will be moved to the waiting queue of the associated monitor, or directly to the ready queue if it is a free event. A call to this function will cause the suspend-hook of the task to be executed.

Example

Example of an event-driven code function:

```
function [exectime, data] = ctrl(seg, data)
switch seg,
 case 1,
   ttWait('Event1');
   exectime = 0.0;
 case 2,
   performCalculations;
   exectime = 0.001;
 case 3,
   ttSetNextSegment(1); % loop and wait for new event
   exectime = 0.0;
end
```

The event above may, e.g., be notified from an interrupt handler associated with an external interrupt channel or the network receive channel of the kernel block.

See Also

`ttEnterMonitor`, `ttCreateEvent`, `ttNotify`, `ttNotifyAll`

15. References

Andersson, M., D. Henriksson, A. Cervin, and K.-E. Årzén (2005): "Simulation of wireless networked control systems." In *44th IEEE Conference on Decision and Control, and the European Control Conference, CDC-ECC '05*. Seville, Spain.

Åström, K. J. and T. Hägglund (1995): *PID Controllers: Theory, Design, and Tuning*. Instrument Society of America, Research Triangle Park, North Carolina.

Bollella, G., B. Brosgol, P. Dibble, S. Furr, J. Gosling, D. Hardin, and M. Turnbull (2000): *The Real-Time Specification for Java*. Addison-Wesley.

Cervin, A., D. Henriksson, B. Lincoln, J. Eker, and K.-E. Årzén (2003): "How does control timing affect performance? Analysis and simulation of timing using Jitterbug and TrueTime." *IEEE Control Systems Magazine*, **23:3**, pp. 16–30.

Henriksson, D., A. Cervin, and K.-E. Årzén (2002): "Truetime: Simulation of control loops under shared computer resources." In *Proceedings of the 15th IFAC world congress*.

Henriksson, D., A. Cervin, and K.-E. Årzén (2003): "Truetime: Real-time control system simulation with matlab/simulink." In *Proceedings of the Nordic MATLAB Conference*.

Ohlin, M. (2006): "Feedback linux scheduling and a simulation tool for wireless control." Licentiate Thesis ISRN LUTFD2/TFRT--3240--SE. Department of Automatic Control, Lund University, Sweden.

Perkins, C. E. and E. M. Royer (1999): "Ad-hoc on-demand distance vector routing." In *Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, pp. 90–100. New Orleans, LA.

Perkins, C. E. and E. M. Royer (2003): "Ad-hoc on-demand distance vector (AODV) routing." Request for Comments: http://www.ietf.org/rfc/rfc3561.txt.

The Mathworks (2001): *Simulink: A Program for Simulating Dynamic Systems – User's Guide*. The MathWorks Inc., Natick, MA.