

Functional Mock-up Interface for  
Model Exchange and Co-Simulation

Document version: 2.0.4

Nov. 10th 2022

This document defines the Functional Mock-up Interface (FMI), version 2.0.4. This is a maintenance release for FMI 2.0. FMI is a tool-independent standard to support both model exchange and co-simulation of dynamic models using a combination of XML files and C code (either compiled in DLL/shared libraries or in source code). The first version, FMI 1.0, was published in 2010. The FMI development was initiated by Daimler AG with the goal to improve the exchange of simulation models between suppliers and OEMs. As of today, development of the standard continues through the participation of many companies and research institutes. FMI 2.0 is supported by over 100 tools and is used by automotive and non-automotive organizations throughout Europe, Asia and North America.

The downloads page (<https://fmi-standard.org/downloads>/) provides this specification, as well as supporting C header and XML schema files and an FMI compliance checker. In addition, sample models (exported from different tools in FMI format) are provided to assist tool vendors to ensure compatibility with other tools, as well as a test suite to check whether connected FMUs (Functional Mock-up Units) are appropriately handled by a tool.

Contact the FMI development group at [contact@fmi-standard.org](mailto:contact@fmi-standard.org).

History / Road Map

|  |  |  |
| --- | --- | --- |
| Version | Date | Remarks |
| 1.0 | 2010-01-26 | First version of FMI for Model Exchange |
| 1.0 | 2010-10-12 | First version of FMI for Co-Simulation |
| 2.0 | 2014-07-25 | Second version of FMI for Model Exchange and Co-Simulation |
| 2.0.1 | 2019-10-02 | Bugfix/maintenance release of FMI for Model Exchange and Co-Simulation 2.0 |
| 2.0.2 | 2020-12-15 | Bugfix/maintenance release of FMI for Model Exchange and Co-Simulation 2.0 |
| 2.0.3 | 2021-11-15 | Bugfix/maintenance release of FMI for Model Exchange and Co-Simulation 2.0 |
| 2.0.4 | 2022-11-10 | Bugfix/maintenance release of FMI for Model Exchange and Co-Simulation 2.0 Backporting of “orthogonal” features “Terminals and Icons” and “Build Configuration” from FMI 3.0 |

Please, report issues that you find with this specification to the public FMI issue tracking system:

<https://github.com/modelica/fmi-standard/issues/>

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If you have improvement suggestions, please send them to the FMI development group at <mailto:contact@fmi-standard.org>.

**Abstract**

This document defines the Functional Mock-up Interface (FMI), version 2.0.4 to (a) exchange dynamic models between tools and (b) define tool coupling for dynamic system simulation environments.

*FMI for Model Exchange (chapter 3)*

The intention is that a modeling environment can generate a C code representation of a dynamic system model that can be utilized by other modeling and simulation environments. Models are described by differential, algebraic and discrete equations with time-, state- and step-events. If the C code describes a continuous system, this system is solved with the integrators of the environment where it is used. The models treated by this interface can be large for usage in offline or online simulation, or they can be used in embedded control systems on microprocessors.

*FMI for Co-Simulation (chapter 4)*

The intention is to provide an interface standard for coupling of simulation tools in a co-simulation environment. The data exchange between subsystems is restricted to discrete communication points. In the time between two communication points, the subsystems are solved independently from each other by their individual solver. Master algorithms control the data exchange between subsystems and the synchronization of all simulation solvers (slaves). Simple master algorithms, as well as more sophisticated ones are both supported. Note that the master algorithm itself is *not* part of the FMI standard.

*FMI Common Concepts (chapter 2)*

The two interface standards have many parts in common. In particular, it is possible to utilize several instances of a model and/or a co-simulation tool and to connect them together. The interfaces are independent of the target environment because no header files are used that depend on the target environment (with exception of the data types of the target platform). This allows generating one dynamic link library that can be utilized in any environment on the same platform. A model, a co-simulation slave or the coupling part of a tool, is distributed in one ZIP file called FMU (Functional Mock-up Unit) that contains several files:

1. An XML file contains the definitions of all exposed variables in the FMU and other static information. It is then possible to run the FMU on a target system without this information, in other words with no unnecessary overhead.
2. All required model equations or the access to co-simulation tools are provided with a small set of easy-to-use C functions. A new caching technique allows a more efficient evaluation of the model equations than in other approaches. These C functions can either be provided in source and/or binary form. Binary forms for different platforms can be included in the same FMU ZIP file.
3. The model equations or the co-simuation tool can be either provided directly in the FMU, or the FMU contains only a generic communication module that communicates with an external tool that evaluates or simulates the model. In the XML file, information about the capabilities of the FMU are present, for example to characterize the ability of a co-simulation slave to support advanced master algorithms such as the usage of variable communication step sizes, higher order signal extrapolation, or others.
4. Further data can be included in the FMU ZIP file, especially a model icon (bitmap file), documentation files, maps and tables needed by the FMU, and/or all object libraries or dynamic link libraries that are utilized.

A growing set of tools supports FMI. The actual list of tools is available at:

<https://www.fmi-standard.org/tools>

**About FMI 2.0.4**

FMI 2.0.4 is a maintenance release   
FMUs created according to FMI 2.0.4 are valid FMUs according to FMI 2.0, 2.0.1, 2.0.2 and 2.0.3.   
FMI 2.0.4 contains small bugfixes and two backports from FMI 3.0:

* Terminals and Icons
* - Build configuration

These are new features compared to FMI 2.0.3, but are “orthogonal” extensions that do not interfere with FMI 2.0 behaviour.

**About FMI 2.0.3**

FMI 2.0.3 is a maintenance release with no new functional changes compared to FMI 2.0, 2.0.1, 2.0.2 FMUs created according to FMI 2.0.2 are valid FMUs according to FMI 2.0 or 2.0.1.   
FMI 2.0.3 introduces minor clarifications that are mainly findings from the FMI3.0 development.

**About FMI 2.0.2**

FMI 2.0.2 is a maintenance release with no new functional changes compared to FMI 2.0 or 2.0.1. FMUs created according to FMI 2.0.2 are valid FMUs according to FMI 2.0 or 2.0.1.   
FMI 2.0.2. introduces the “/extra” directory as a standardized place to provide additional information for an FMU according to layered standards. This is does not change the behaviour of the FMU and clarifies the storage location for additional files (even after the creation of the FMU), e.g., required by layered standards.

**About FMI 2.0.1**

FMI 2.0.1 is a maintenance release with no new features compared to FMI 2.0. FMUs created according to FMI 2.0.1 are valid FMUs according to FMI 2.0.

**About FMI 2.0**

FMI 2.0 was a major enhancement to FMI 1.0 that merges the FMI 1.0 Model Exchange and Co-Simulation standards and incorporates many improvements, often due to practical experience when using the FMI 1.0 standards. New features are usually optional (need neither be supported by the tool that exports an FMU, nor by the tool that imports an FMU). Details are provided in appendix A.3.1.

**Conventions used in this Document**

* Non-normative text is given in square brackets in italic font: [*especially examples are defined in this style.*].
* Arrays appear in two forms:
  + In the end-user/logical view, one- and two-dimensional arrays are used. Here the convention of linear algebra, the control community and the most important tools in this area is utilized. In other words, the first element along one dimension starts at index one. In all these cases, the starting index is also explicitly mentioned at the respective definition of the array. For example, in the modelDescription.xml file, the set of exposed variables is defined as ordered sets where the first element is referenced with index one (these indices are, for example, used to define the sparseness structure of partial derivative matrices).
  + In the implementation view, one-dimensional C-arrays are used. In order to access an array element the C-convention is used. For example, the first element of input argument x for function setContinuousStates(..) is x[0].

*[Clarification for FMI 2.0.2: In the structured naming convention both 0- and 1-based array indexing is allowed.]*

**FMI 2.0 Implementation Help**

If you plan to export or import models in FMI 2.0 format, you may find the following tools/models helpful for your development (available from <https://fmi-standard.org/downloads>):

* **Reference FMUs**  
  A set of hand-coded FMUs for development, testing and debugging of the Functional Mock-up Interface available at <https://github.com/modelica/Reference-FMUs/>
* **FMU Compliance Checker**   
  Free software to check whether an FMI model is compliant to the FMI standard
* **FMUs from other tools**  
  In order to test the import of FMI models from other vendors in your tool, a set of test FMUs is provided.
* **Library to test connected FMUs**  
  Free Modelica library to test difficult cases of connected FMI models.
* **FMU Software Development Kit**  
  Free software development kit by QTronic to demonstrate basic use of FMI.
* **FMI Library**Free software package by Modelon that enables integration of FMI models in applications.

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# Overview

The FMI (Functional Mock-up Interface) defines an interface to be implemented by an executable called an FMU (Functional Mock-up Unit). The FMI functions are used (called) by a simulation environment to create one or more instances of the FMU and to simulate them, typically together with other models. An FMU may either have its own solvers (FMI for Co-Simulation, chapter 4) or require the simulation environment to perform numerical integration (FMI for Model Exchange, chapter 3). The goal of this interface is that the calling of an FMU in a simulation environment is reasonably simple. No provisions are provided in this document for how to generate an FMU from a modeling environment.

The FMI for Model Exchange interface defines an interface to the model of a dynamic system described by differential, algebraic and discrete-time equations. It provides an interface to evaluate these equations as needed in different simulation environments, as well as in embedded control systems, with explicit or implicit integrators, and fixed or variable step-size. The interface is designed to allow the description of large models.

The FMI for Co-Simulation interface is designed both for the coupling of simulation tools (simulator coupling, tool coupling), and coupling with subsystem models, which have been exported by their simulators together with its solvers as runnable code. The goal is to compute the solution of time-dependent coupled systems consisting of subsystems that are continuous in time (model components that are described by differential-algebraic equations) or are time-discrete (model components that are described by difference equations, for example discrete controllers). In a block representation of the coupled system, the subsystems are represented by blocks with (internal) state variables **x**(*t*) that are connected to other subsystems (blocks) of the coupled problem by subsystem inputs **u**(*t*) and subsystem outputs **y**(*t*).

In case of tool coupling, the modular structure of coupled problems is exploited in all stages of the simulation process beginning with the separate model setup and pre-processing for the individual subsystems in different simulation tools. During time integration, the simulation is again performed independently for all subsystems restricting the data exchange between subsystems to discrete *communication points*. Finally, the visualization and post-processing of simulation data is done individually for each subsystem in its own native simulation tool.

The two interfaces have large parts in common. These parts are defined in chapter 2. In particular:

* FMI Application Programming Interface (C)  
  All required equations or tool coupling computations are evaluated by calling standardized C functions. C is used because it is the most portable programming language today and is the only programming language that can be utilized in all embedded control systems.
* FMI Description Schema (XML)  
  The schema defines the structure and content of an XML file generated by a modeling environment. This XML file contains the definition of all variables of the FMU in a standardized way. It is then possible to run the C code in an embedded system without the overhead of the variable definition (the alternative would be to store this information in the C code and access it via function calls, but this is neither practical for embedded systems nor for large models). Furthermore, the variable definition is a complex data structure and tools should be free to determine how to represent this data structure in their programs. The selected approach allows a tool to store and access the variable definitions (without any memory or efficiency overhead of standardized access functions) in the programming language of the simulation environment, such as C++, C#, Java, or Python. Note that there are many free and commercial libraries in different programming languages to read XML files into an appropriate data structure. See for example [http://en.wikipedia.org/wiki/XML#Parsers](http://en.wikipedia.org/wiki/Xml#Parsers) and especially the efficient open source parser SAX (<http://sax.sourceforge.net/>, <http://en.wikipedia.org/wiki/Simple_API_for_XML>).

An FMU (in other words a model without integrators, a runnable model with integrators, or a tool coupling interface) is distributed in one ZIP file. The ZIP file contains (more details are given in section 2.3):

* The FMI Description File (in XML format).
* The C sources of the FMU, including the needed run-time libraries used in the model, and/or binaries for one or several target machines, such as Windows dynamic link libraries (.dll) or Linux shared object libraries (.so). The latter solution is especially used if the FMU provider wants to hide the source code to secure the contained know-how or to allow a fully automatic import of the FMU in another simulation environment. An FMU may contain physical parameters or geometrical dimensions, which should not be open. On the other hand, some functionality requires source code.
* Additional FMU data (such as tables or maps) in FMU specific file formats.

A schematic view of an FMU is shown in Figure 1:

**u**

**y**

Enclosing Model

**v**



|  |  |
| --- | --- |
| *t* | time |
| **p** | parameters of type Real, Integer, Boolean, String |
| **u** | inputs of type Real, Integer, Boolean, String |
| **v** | all exposed variables |
| **y** | outputs of type Real, Integer, Boolean, String |

FMU instance   
(model exchange or co-simulation)

Figure 1: Data flow between the environment and an FMU. For details, see chapters 3 and 4.   
Blue arrows: Information provided by the FMU.  
Red arrows: Information provided to the FMU.

Publications for FMI are available from https://fmi-standard.org/literature/, especially *Blochwitz et.al.* [*2011*](http://www.ep.liu.se/ecp/063/013/ecp11063013.pdf) *and* [*2012*](http://www.ep.liu.se/ecp/076/017/ecp12076017.pdf).

## Properties and Guiding Ideas

In this section, properties are listed and some principles are defined that guided the low-level design of the FMI. This shall increase self consistency of the interface functions. The listed issues are sorted, starting from high-level properties to low-level implementation issues.

*Expressivity*: The FMI provides the necessary features that Modelica®, Simulink® and SIMPACK® models[[1]](#footnote-1) can be transformed to an FMU.

*Stability*: The FMI is expected to be supported by many simulation tools worldwide. Implementing such support is a major investment for tool vendors. Stability and backwards compatibility of the FMI has therefore high priority. To support this, the FMI defines 'capability flags' that will be used by future versions of the FMI to extend and improve the FMI in a backwards compatible way, whenever feasible.

*Implementation*: FMUs can be written manually or can be generated automatically from a modeling environment. Existing manually coded models can be transformed manually to a model according to the FMI standard.

*Processor independence*: It is possible to distribute an FMU without knowing the target processor. This allows an FMU to run on a PC, a Hardware-in-the-Loop simulation platform or as part of the controller software of an ECU, for example, as part of an AUTOSAR SWC. Keeping the FMU independent of the target processor increases the usability of the FMU and is even required by the AUTOSAR software component model. Implementation: Using a textual FMU (distribute the C source of the FMU).

*Simulator independence*: It is possible to compile, link and distribute an FMU without knowing the target simulator. Reason: The standard would be much less attractive otherwise, unnecessarily restricting the later use of an FMU at compile time and forcing users to maintain simulator specific variants of an FMU. Implementation: Using a binary FMU. When generating a binary FMU such as a Windows dynamic link library (.dll) or a Linux shared object library (.so), the target operating system and eventually the target processor must be known. However, no run-time libraries, source files or header files of the target simulator are needed to generate the binary FMU. As a result, the binary FMU can be executed by any simulator running on the target platform (provided the necessary licenses are available, if required from the model or from the used run-time libraries).

*Small run-time overhead*: Communication between an FMU and a target simulator through the FMI does not introduce significant run-time overhead. This is achieved by a new caching technique (to avoid computing the same variables several times) and by exchanging vectors instead of scalar quantities.

*Small footprint*: A compiled FMU (the executable) is small. Reason: An FMU may run on an ECU (Electronic Control Unit, for example, a microprocessor), and ECUs have strong memory limitations. This is achieved by storing signal attributes (names, units, etc.) and all other static information not needed for model evaluation in a separate text file (= Model Description File) that is not needed on the microprocessor where the executable might run.

*Hide data structure*: The FMI for Model Exchange does not prescribe a data structure (a C struct) to represent a model. Reason: the FMI standard shall not unnecessarily restrict or prescribe a certain implementation of FMUs or simulators (whichever contains the model data) to ease implementation by different tool vendors.

*Support many and nested FMUs*: A simulator may run many FMUs in a single simulation run and/or multiple instances of one FMU. The inputs and outputs of these FMUs can be connected with direct feedthrough. Moreover, an FMU may contain nested FMUs.

*Numerical Robustness*: The FMI standard allows that problems which are numerically critical (for example, time and state events, multiple sample rates, stiff problems) can be treated in a robust way.

*Hide cache:* A typical FMU will cache computed results for later reuse. To simplify usage and to reduce error possibilities by a simulator, the caching mechanism is hidden from the usage of the FMU. Reason: First, the FMI should not force an FMU to implement a certain caching policy. Second, this helps to keep the FMI simple. Implementation: The FMI provides explicit methods (called by the FMU environment) for setting properties that invalidate cached data. An FMU that chooses to implement a cache may maintain a set of 'dirty' flags, hidden from the simulator. A get method, for example to a state, will then either trigger a computation, or return cached data, depending on the value of these flags.

*Support numerical solvers*: A typical target simulator will use numerical solvers. These solvers require vectors for states, derivatives and zero-crossing functions. The FMU directly fills the values of such vectors provided by the solvers. Reason: minimize execution time. The exposure of these vectors conflicts somewhat with the 'hide data structure' requirement, but the efficiency gain justifies this.

*Explicit signature*: The intended operations, argument types and return values are made explicit in the signature. For example, an operator (such as 'compute\_derivatives') is not passed as an int argument but a special function is called for this. The 'const' prefix is used for any pointer that should not be changed, including 'const char\*' instead of 'char\*'. Reason: the correct use of the FMI can be checked at compile time and allows calling of the C code in a C++ environment (which is much stricter on ‘const’ than C is). This will help to develop FMUs that use the FMI in the intended way.

*Few functions*: The FMI consists of a few, 'orthogonal' functions, avoiding redundant functions that could be defined in terms of others. Reason: This leads to a compact, easy-to-use, and hence attractive API with a compact documentation.

*Error handling*: All FMI methods use a common set of methods to communicate errors.

*Allocator must free*: All memory (and other resources) allocated by the FMU are freed (released) by the FMU. Likewise, resources allocated by the simulator are released by the simulator. Reason: this helps to prevent memory leaks and run-time errors due to incompatible run-time environments for different components.

*Immutable strings*: All strings passed as arguments or returned are read-only and must not be modified by the receiver. Reason: This eases the reuse of strings.

*Named list elements*: All lists defined in the fmiModelDescription.xsd XML schema file have a String attribute name to a list element. This attribute must be unique with respect to all other name attributes of the *same* list.

*Use C*: The FMI is encoded using C, not C++. Reason: Avoid problems with compiler and linker dependent behavior. Run FMU on embedded target.

This version of the functional mock-up interface does not have the following desirable properties. They might be added in a future version.

* The FMI for Model Exchange is for ordinary differential equations (ODEs) in state space form. It is not for a general differential-algebraic equation system. However, algebraic equation systems inside the FMU are supported (for example, the FMU can report to the environment to re-run the current step with a smaller step size since a solution could not be found for an algebraic equation system).
* Special features that might be useful for multibody system programs, like SIMPACK, are not included.
* The interface is for simulation and for embedded systems. Properties that might be additionally needed for trajectory optimization, for example, derivatives of the model with respect to parameters during continuous integration are not included.
* No explicit definition of the variable hierarchy in the XML file.
* The number of states and number of event indicators are fixed for an FMU and cannot be changed.

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# FMI Common Concepts for Model Exchange and Co-Simulation

The concepts defined in this chapter are common for “model exchange” and “co-simulation”. In both cases, FMI defines an input/output block of a dynamic model where the distribution of the block, the platform dependent header file, several access functions, as well as the schema files are identical. The definitions that are specific to the particular cases are defined in chapters 3 and 4.

Below, the term **FMU** (Functional Mock-up Unit) will be used as common term for a model in the “FMI for model exchange” format, or a co-simulation slave in the “FMI for co-simulation” format. Note that the interface supports several instances of one FMU.

## FMI Application Programming Interface

This section contains the common interface definitions to execute functions of an FMU from a C program.

Note that the following general properties hold for an FMU:

* FMI functions of one instance do not need to be thread-safe.   
  [*For example, if the functions of one instance of an FMU are accessed from more than one thread, the multi-threaded environment that uses the FMU must guarantee that the calling sequences of functions defined in section 3.2.3 and section 4.2.4. are used. The FMU itself does not implement any services to support this.*]
* FMI functions must not change global settings which affect other processes/threads. An FMI function may change settings of the process/thread in which it is called (such as floating point control registers), provided these changes are restored before leaving the function or before a callback function is called.   
  [*This property ensures that functions of different FMU instances can be called safely in any order. Additionally, they can be called in parallel provided the functions are called in different process/threads. If an FMI function changes for example the floating point control word of the CPU, it must restore the previous value before return of the function. For x86 CPUs, the floating point control word is set using the fldcw instruction. This can be used to switch on additional exceptions such as "floating point division by zero". An FMU might temporarily change the floating point control word and get notified on floating point exceptions internally, but has to restore the flag and clear the floating point status word before return of the respective FMI function.*]

### Header Files and Naming of Functions

Three header files are provided that define the interface of an FMU. In all header files the convention is used that all C function and type definitions start with the prefix “fmi2”:

* “fmi2TypesPlatform.h”   
  contains the type definitions of the input and output arguments of the functions. This header file must be used both by the FMU and by the target simulator. If the target simulator has different definitions in the header file (for example, “**typedef float** fmi2Real” instead of “**typedef double** fmi2Real”), then the FMU needs to be recompiled with the header file used by the target simulator. Note that the header file platform for which the model was compiled can be inquired in the target simulator with fmi2GetTypesPlatform (see section 2.1.4).   
  [*Example for a definition in this header file:*  
   **typedef double** fmi2Real;  
  ]
* “fmi2FunctionTypes.h”  
  contains **typedef** definitions of all function prototypes of an FMU. When dynamically loading an FMU, these definitions can be used to type-cast the function pointers to the respective function definition. [*Example for a definition in this header file:*  
   **typedef** fmi2Status fmi2SetTimeTYPE(fmi2Component, fmi2Real);  
  ]
* “fmi2Functions.h”  
  contains the function prototypes of an FMU that can be accessed in simulation environments and that are defined in chapters 2, 3, and 4. This header file includes “fmi2TypesPlatform.h” and “fmi2FunctionTypes.h”. Note that the header file version number for which the model was compiled, can be inquired in the target simulator with fmi2GetVersion (see section 2.1.4).   
  [*Example for a definition in this header file[[2]](#footnote-2):*  
   FMI2\_Export fmi2SetTimeTYPE fmi2SetTime;  
  ]

The goal is that both textual and binary representations of FMUs are supported and that several FMUs might be present at the same time in an executable (for example, FMU A may use an FMU B). In order for this to be possible, the names of the functions in different FMUs must be different, or function pointers must be used. To support the first variant, macros are provided in “fmi2Functions.h” to build the actual function names by using a function prefix that depends on how the FMU is shipped.   
[*These macros can be defined differently in a target specific variant of* “fmi2Functions.h“ *to adjust them to the requirements of the supported compilers and platforms of the importing tool.*]An FMU C file must include at the beginning a #define of FMI2\_FUNCTION\_PREFIX as the `modelIdentifier` attribute defined in <fmiModelDescription><ModelExchange> or <fmiModelDescription><CoSimulation>together with \_ at the end (see sections 3.3.1 and 4.3.1).  
This #define must be directly follwed with an #include “fmi2Functions.h“ statement.

Typically, FMU functions are used as follows:

// FMU is shipped with C source code, or with static link library

**#define** FMI2\_FUNCTION\_PREFIX MyModel\_

**#include** "fmi2Functions.h"

< usage of the FMU functions >

// FMU is shipped with DLL/SharedObject

**#include** "fmi2Functions.h"

< usage of the FMU functions >

A function that is defined as “fmi2GetReal” is changed by the macros to a function name as follows:

* If the FMU is shipped with C source code or with static link library:   
  The constructed function name is “MyModel\_fmi2GetReal”. In other words the function name is prefixed with the model name and an “\_”.A simulation environment can therefore construct the relevant function names by generating code for the actual function call. In case of a static link library, the name of the library is MyModel.lib on Windows and libMyModel.a on Linux; in other words the “modelIdentifier” attribute is used as library name.
* If the FMU is shipped with DLL/SharedObject:  
  The constructed function name is “fmi2GetReal”, in other words, it is not changed. [*This can be realized in the case of a source code FMU with a target-specific version of* “fmi2Functions.h” *that does not use* FMI2\_FUNCTION\_PREFIX *to construct the function names.*   
  *[New in FMI 2.0.4:]* Using the standard-supplied version of “fmi2Functions.h”, the same effect can be achieved by defining the “FMI2\_OVERRIDE\_FUNCTION\_PREFIX“ precompiler macro prior to the inclusion of the `fmi2Functions.h` header, for example using precompiler command-line flags.] A simulation environment will then dynamically load this library and will explicitly import the function symbols by providing the FMI function names as strings. The name of the library is MyModel.dll on Windows or MyModel.so on Linux; in other words the “modelIdentifier” attribute is used as library name.

[*An FMU can be optionally shipped so that it basically contains only the communication to another tool (needsExecutionTool = true, see section 4.3.1). This is particularily common for co-simulation tasks. In FMI 1.0, the function names are always prefixed with the model name and therefore a DLL/Shared Object has to be generated for every model. FMI 2.0 improves this situation since model names are no longer used as prefix in case of DLL/Shared Objects: Therefore one DLL/Shared Object can be used for all models in case of tool coupling. If an FMU is imported into a simulation environment, this is usually performed dynamically (based on the FMU name, the corresponding FMU is loaded during execution of the simulation environment) and then it does not matter whether a model name is prefixed or not.*]

Since “modelIdentifier” is used as prefix of a C-function name it must fulfill the restrictions on C-function names (only letters, digits and/or underscores are allowed). [*For example, if modelName = “A.B.C“, then modelIdentifier might be “A\_B\_C“.*] Since “modelIdentifier” is also used as name in a file system, it must also fulfill the restrictions of the targeted operating system. Basically, this means that it should be short. For example, the Windows API only supports full path-names of a file up to 260 characters (see: <http://msdn.microsoft.com/en-us/library/aa365247%28VS.85%29.aspx>).

### Platform Dependent Definitions (fmi2TypesPlatform.h)

To simplify porting, no C types are used in the function interfaces, but the alias types are defined in this section. All definitions in this section are provided in the header file “fmi2TypesPlatform.h”.

|  |  |
| --- | --- |
| **#define** fmi2TypesPlatform "default" | |
|  | A definition that can be inquired with fmi2GetTypesPlatform. It is used to uniquely identify the header file used for compilation of a binary. [*The “default” definition below is suitable for most common platforms. It is recommended to use this “default” definition for all binary FMUs. Only for source code FMUs, a change might be useful in some cases.*]:  fmi2Component : an opaque object pointer  fmi2ComponentEnvironment: an opaque object pointer  fmi2FMUstate : an opaque object pointer  fmi2ValueReference : value handle type  fmi2Real : real data type  fmi2Integer : integer data type  fmi2Boolean : datatype to be used with fmi2True and  fmi2False  fmi2Char : character data type (size of one character)  fmi2String : pointer to a vector of fmi2Char characters  ('\0' terminated, UTF-8 encoded)  fmi2Byte : smallest addressable unit of the machine  (typically one byte) |
| **typedef** **void**\* fmi2Component; | |
|  | This is a pointer to an FMU specific data structure that contains the information needed to process the model equations or to process the co-simulation of the respective slave. This data structure is implemented by the environment that provides the FMU; in other words, the calling environment does not know its content, and the code to process it must be provided by the FMU generation environment and must be shipped with the FMU. |
| **typedef** **void**\* fmi2ComponentEnvironment; | |
|  | This is a pointer to a data structure in the simulation environment that calls the FMU. Using this pointer, data from the modelDescription.xml file [*(for example, mapping of valueReferences to variable names)*] can be transferred between the simulation environment and the logger function (see section 2.1.5). |
| **typedef** **void**\* fmi2FMUstate; | |
|  | This is a pointer to a data structure in the FMU that saves the internal FMU state of the actual or a previous time instant. This allows to restart a simulation from a previous FMU state (see section 2.1.8). |
| **typedef** **unsigned int** fmi2ValueReference; | |
|  | This is a handle to a (base type) variable value of the model. Handle and base type (such as fmi2Real) uniquely identify the **value** of a variable. Variables of the same base type that have the same handle, always have identical values, but other parts of the variable definition might be different [*(for example, min/max attributes)*].  All structured entities, such as records or arrays, are “flattened” into a set of scalar values of type fmi2Real, fmi2Integer, etc. An fmi2ValueReference references one such scalar. The coding of fmi2ValueReference is a “secret” of the environment that generated the FMU. The interface to the equations only provides access to variables via this handle. Extracting concrete information about a variable is specific to the used environment that reads the Model Description File in which the value handles are defined.  If a function in the following sections is called with a wrong “fmi2ValueReference” value [*(for example, setting a constant with a* fmi2SetReal(..) *function call)*], then the function has to return with an error (fmi2Status = fmi2Error, see section 2.1.3). |
| **typedef** **double** fmi2Real ; // Data type for floating point real numbers  **typedef** **int** fmi2Integer; // Data type for signed integer numbers  **typedef** **int**  fmi2Boolean; // Data type for Boolean numbers   // (only two values: fmi2False, fmi2True)  **typedef** **char** fmi2Char; // Data type for one character  **typedef** **const** fmi2Char\* fmi2String; // Data type for character strings   // (′\0′ terminated, UTF-8 encoded)  **typedef char** fmi2Byte; // Data type for the smallest addressable  // unit, typically one byte  **#define** fmi2True 1  **#define** fmi2False 0 | |
|  | These are the basic data types used in the interfaces of the C functions. More data types might be included in future versions of the interface. In order to keep flexibility, especially for embedded systems or for high performance computers, the exact data types or the word length of a number are not standardized. Instead, the precise definition (in other words, the header file “fmi2TypesPlatform.h”) is provided by the environment where the FMU shall be used. In most cases, the definition above will be used. If the target environment has different definitions and the FMU is distributed in binary format, it must be newly compiled and linked with this target header file.  If an fmi2String variable is passed as input argument to an FMI function and the FMU needs to use the string later, the FMI function must copy the string before it returns and store it in the internal FMU memory, because there is no guarantee for the lifetime of the string after the function has returned.  If an fmi2String variable is passed as output argument from an FMI function and the string shall be used in the target environment, the target environment must copy the whole string (not only the pointer). The memory of this string may be deallocated by the next call to any of the FMI interface functions. (The string memory might also be just a buffer that is reused.) |

### Status Returned by Functions

This section defines the “status” flag (an enumeration of type fmi2Status defined in file “fmi2FunctionTypes.h”) that is returned by all functions to indicate the success of the function call:

|  |
| --- |
| **typedef** **enum** { fmi2OK,  fmi2Warning,  fmi2Discard,  fmi2Error,  fmi2Fatal,  fmi2Pending } fmi2Status; |
| Status returned by functions. The status has the following meaning  fmi2OK – all well  fmi2Warning – things are not quite right, but the computation can continue. Function “logger” was called in the model (see below), and it is expected that this function has shown the prepared information message to the user.  fmi2Discard – this return status is only possible if explicitly defined for the corresponding function[[3]](#footnote-3) (ModelExchange: fmi2SetReal, fmi2SetInteger, fmi2SetBoolean, fmi2SetString, fmi2SetContinuousStates, fmi2GetReal, fmi2GetDerivatives, fmi2GetContinuousStates, fmi2GetEventIndicators; CoSimulation: fmi2SetReal, fmi2SetInteger, fmi2SetBoolean, fmi2SetString, fmi2DoStep, fmiGetXXXStatus):   For “model exchange”: It is recommended to perform a smaller step size and evaluate the model equations again, for example because an iterative solver in the model did not converge or because a function is outside of its domain (for example sqrt(<negative number>)). If this is not possible, the simulation has to be terminated.   For “co-simulation”: fmi2Discard is returned also if the slave is not able to return the required status information. The master has to decide if the simulation run can be continued.  In both cases, function “logger” was called in the FMU (see below) and it is expected that this function has shown the prepared information message to the user if the FMU was called in debug mode (loggingOn = fmi2True). Otherwise, “logger” should not show a message.  fmi2Error – the FMU encountered an error. The simulation cannot be continued with this FMU instance. If one of the functions returns fmi2Error, it can be tried to restart the simulation from a formerly stored FMU state by calling fmi2SetFMUstate. This can be done if the capability flag canGetAndSetFMUstate is true and fmi2GetFMUstate was called before in non-erroneous state. If not, the simulation cannot be continued and fmi2FreeInstance or fmi2Reset must be called afterwards.[[4]](#footnote-4)  Further processing is possible after this call; especially other FMU instances are not affected. Function “logger” was called in the FMU (see below), and it is expected that this function has shown the prepared information message to the user.  fmi2Fatal – the model computations are irreparably corrupted for all FMU instances. [*For example, due to a run-time exception such as access violation or integer division by zero during the execution of an fmi function*]. Function “logger” was called in the FMU (see below), and it is expected that this function has shown the prepared information message to the user. It is not possible to call any other function for any of the FMU instances.  fmi2Pending – this status is returned only from the co-simulation interface, if the slave executes the function in an asynchronous way. That means the slave starts to compute but returns immediately. The master has to call fmi2GetStatus(..., fmi2DoStepStatus) to determine if the slave has finished the computation. Can be returned only by fmi2DoStep and by fmi2GetStatus (see section 4.2.3). |

### Inquire Platform and Version Number of Header Files

This section documents functions to inquire information about the header files used to compile its functions.

|  |  |
| --- | --- |
| **const char**\* fmi2GetTypesPlatform(void); | |
|  | Returns the string to uniquely identify the “fmi2TypesPlatform.h” header file used for compilation of the functions of the FMU. The function returns a pointer to a static string specified by “fmi2TypesPlatform” defined in this header file. The standard header file, as documented in this specification, has fmi2TypesPlatform set to “default” (so this function usually returns “default”). |
| **const char**\* fmi2GetVersion(void); | |
|  | Returns the version of the “fmi2Functions.h” header file which was used to compile the functions of the FMU. The function returns “fmiVersion” which is defined in this header file. The standard header file as documented in this specification has version “2.0” (so this function usually returns “2.0”). |

### Creation, Destruction and Logging of FMU Instances

This section documents functions that deal with instantiation, destruction and logging of FMUs.

|  |  |
| --- | --- |
| fmi2Component fmi2Instantiate(fmi2String instanceName,  fmi2Type fmuType,  fmi2String fmuGUID,  fmi2String fmuResourceLocation,  **const** fmi2CallbackFunctions\* functions,  fmi2Boolean visible,  fmi2Boolean loggingOn);  **typedef** **enum** {fmi2ModelExchange,  fmi2CoSimulation  }fmi2Type; | |
|  | The function returns a new instance of an FMU. If a null pointer is returned, then instantiation failed. In that case, “functions->logger” is called with detailed information about the reason. An FMU can be instantiated many times (provided capability flag canBeInstantiatedOnlyOncePerProcess = false).  This function must be called successfully before any of the following functions can be called. For co-simulation, this function call has to perform all actions of a slave which are necessary before a simulation run starts (for example, loading the model file, compilation...).  Argument instanceName is a unique identifier for the FMU instance. It is used to name the instance, for example, in error or information messages generated by one of the fmi2XXX functions. It is not allowed to provide a null pointer and this string must be non-empty (in other words, must have at least one character that is no white space). [*If only one FMU is simulated, as instanceName attribute modelName or <ModelExchange/CoSimulation modelIdentifier=”..”> from the XML schema fmiModelDescription might be used.*]  Argument fmuType defines the type of the FMU:   * = fmi2ModelExchange: FMU with initialization and events; between events simulation of continuous systems is performed with external integrators from the environment (see section 3). * = fmi2CoSimulation: Black box interface for co-simulation (see section 4).   Argument fmuGUID is used to check that the modelDescription.xml file (see section 2.3) is compatible with the C code of the FMU. It is a vendor specific globally unique identifier of the XML file (for example, it is a “fingerprint” of the relevant information stored in the XML file). It is stored in the XML file as attribute “guid” (see section 0) and has to be passed to the fmi2Instantiate function via argument fmuGUID. It must be identical to the one stored inside the fmi2Instantiate function; otherwise the C code and the XML file of the FMU are not consistent with each other. This argument cannot be null.  Argument fmuResourceLocation is a URI according to the [IETF RFC3986](http://datatracker.ietf.org/doc/rfc3986/) syntax to indicate the location to the “resources” directory of the unzipped FMU archive. The following schemes must be understood by the FMU:  Mandatory: “file” with absolute path (either including or omitting the authority component)   * Optional: “http”, “https”, “ftp” * Reserved: “fmi2” for FMI for PLM.   [*Example: An FMU is unzipped in directory “*C:\temp\MyFMU*”,* then fmuResourceLocation = “file:///C:/temp/MyFMU/resources” *or “*file:/C:/temp/MyFMU/resources”*. Function* fmi2Instantiate *is then able to read all needed resources from this directory, for example maps or tables used by the FMU.*]  Argument functions provides callback functions to be used from the FMU functions to utilize resources from the environment (see type fmi2CallbackFunctions below).  Argument visible = fmi2False defines that the interaction with the user should be reduced to a minimum (no application window, no plotting, no animation, etc.). In other words, the FMU is executed in batch mode. If visible = fmi2True, the FMU is executed in interactive mode, and the FMU might require to explicitly acknowledge start of simulation / instantiation / initialization (acknowledgment is non-blocking).  If loggingOn = fmi2True, debug logging is enabled. If loggingOn = fmi2False, debug logging is disabled. [*The FMU enable/disables* LogCategories *which are useful for debugging according to this argument. Which* LogCategories *the FMU sets is unspecified.*] |
| **typedef** **struct** {  **void** (\*logger)(fmi2ComponentEnvironment componentEnvironment,  fmi2String instanceName,  fmi2Status status,  fmi2String category,  fmi2String message, ...);  **void**\* (\*allocateMemory)(**size\_t** nobj, **size\_t** size);  **void** (\*freeMemory) (**void**\* obj);  **void** (\*stepFinished) (fmi2ComponentEnvironment componentEnvironment,  fmi2Status status);  fmi2ComponentEnvironment componentEnvironment;  } fmi2CallbackFunctions; | |
|  | The struct contains pointers to functions provided by the environment to be used by the FMU. It is not allowed to change these functions between fmi2Instantiate(..) and fmi2Terminate(..) calls. Additionally, a pointer to the environment is provided (componentEnvironment) that needs to be passed to the “logger” function, in order that the logger function can utilize data from the environment, such as mapping a valueReference to a string. In the unlikely case that fmi2Component is also needed in the logger, it has to be passed via argument componentEnvironment. Argument componentEnvironment may be a null pointer. The componentEnvironment pointer is also passed to the stepFinished(..) function in order that the environment can provide an efficient way to identify the slave that called stepFinished(..).  In the default fmi2FunctionTypes.h file, typedefs for the function definitions are present to simplify the usage; this is non-normative. The functions have the following meaning:  Function **logger**:  Pointer to a function that is called by the FMU [usually if an fmi2XXX function, does not  behave as desired]. If “status = fmi2OK”, the message is a pure information message.  “instanceName” is the name of the FMU instance that calls this function. “category” is the  category of the message.  The allowed values for “category” are defined in the modelDescription.xml file via the  element “<fmiModelDescription><LogCategories>”, see section 2.2.4. “logger” should  only be called for log categories that were enabled by a call to fmi2SetDebugLogging (see  below) or via “loggingOn = fmi2True” in fmi2Instantiate.  If the FMU does not define any log categories, “category” must be “NULL”.  Argument “message” is a string that contains the message to log. It may contain line-breaks  (“\n”), but should not have a trailing line break and is provided in the same way and with the  same format control as in function “printf” from the C standard library.  *[Typically, this function prints the message and stores it optionally in a log file.]*  All string-valued arguments passed by the FMU to the logger may be deallocated by the  FMU directly after function logger returns.  *[The simulation environment must therefore create copies of these strings, if it needs to access these strings later.]*  Variables are referenced in a message with “#<Type><ValueReference>#” where <Type> is “r” for fmi2Real, “i” for fmi2Integer, “b” for fmi2Boolean and “s” for fmi2String. If character “#”shall be included in the message, it has to be prefixed with “#”, so “#” is an escape character. [*Example:*  *A message of the form*  *“#r1365# must be larger than zero (used in IO channel ##4)”*  *might be changed by the logger function to*  *“body.m must be larger than zero (used in IO channel #4)”*  *if “body.m” is the name of the fmi2Real variable with fmi2ValueReference = 1365.*]  Function **allocateMemory**:  Pointer to a function that is called in the FMU if memory needs to be allocated. If attribute “canNotUseMemoryManagementFunctions = true” in <fmiModelDescription><ModelExchange / CoSimulation>, then function allocateMemory is not used in the FMU and a void pointer can be provided. If this attribute has a value of “false” (which is the default), the FMU must not use malloc, calloc or other memory allocation functions. One reason is that these functions might not be available for embedded systems on the target machine. Another reason is that the environment may have optimized or specialized memory allocation functions. allocateMemory returns a pointer to space for a vector of nobj objects, each of size “size” or NULL, if the request cannot be satisfied. The space is initialized to zero bytes [*(a simple implementation is to use calloc from the C standard library)*].  Function **freeMemory**: Pointer to a function that must be called in the FMU if memory is freed that has been allocated with allocateMemory. If a null pointer is provided as input argument obj, the function shall perform no action [*(a simple implementation is to use free from the C standard library; in ANSI C89 and C99, the null pointer handling is identical as defined here)*]. If attribute “canNotUseMemoryManagementFunctions = true” in <fmiModelDescription><ModelExchange / CoSimulation>, then function freeMemory is not used in the FMU and a null pointer can be provided.  Function **stepFinished**: Optional call back function to signal if the computation of a communication step of a co-simulation slave is finished. A null pointer can be provided. In this case the master must use fmiGetStatus(..) to query the status of fmi2DoStep. If a pointer to a function is provided, it must be called by the FMU after a completed communication step.  *[Note: In FMI 3.0, memory callback functions were removed, because their intended uses failed to materialize and the implementations often had issues.  New in FMI 2.0.2:* *It is discouraged* *to use the memory callback functions.]* |
| **void** fmi2FreeInstance(fmi2Component c); | |
|  | Disposes the given instance, unloads the loaded model, and frees all the allocated memory and other resources that have been allocated by the functions of the FMU interface. If a null pointer is provided for “c”, the function call is ignored (does not have an effect). |
| fmi2Status fmi2SetDebugLogging(fmi2Component c, fmi2Boolean loggingOn,  **sizet** nCategories,   **const** fmi2String categories[]); | |
|  | The function controls the debug logging that is output via the logger callback function by the FMU.  If loggingOn = fmi2True, debug logging is enabled for the log categories specified in  categories, otherwise it is disabled. nCategories defines the length of the argument  categories.  If nCategories == 0, loggingOn applies to all log categories and the value of  categories is undefined.  The allowed values of categories are defined in the modelDescription.xml file via  element “<LogCategories>”, see section 2.2.4. |

### Initialization, Termination, and Resetting an FMU

This section documents functions that deal with initialization, termination, and resetting of an FMU.

|  |  |
| --- | --- |
| fmi2Status fmi2SetupExperiment(fmi2Component c,  fmi2Boolean toleranceDefined,  fmi2Real tolerance,  fmi2Real startTime,  fmi2Boolean stopTimeDefined,  fmi2Real stopTime); | |
|  | Informs the FMU to setup the experiment. This function must be called after fmi2Instantiate and before fmi2EnterInitializationMode is called. Arguments toleranceDefined and tolerance depend on the FMU type:  **fmuType = fmi2ModelExchange:**  If “toleranceDefined = fmi2True”, then the model is called with a numerical integration scheme where the step size is controlled by using “tolerance” for error estimation (usually as relative tolerance). In such a case, all numerical algorithms used inside the model (for example, to solve non-linear algebraic equations) should also operate with an error estimation of an appropriate smaller relative tolerance.  **fmuType = fmi2CoSimulation:**  If “toleranceDefined = fmi2True”, then the communication interval of the slave is controlled by error estimation. In case the slave utilizes a numerical integrator with variable step size and error estimation, it is suggested to use “tolerance” for the error estimation of the internal integrator (usually as relative tolerance).  An FMU for Co-Simulation might ignore this argument.  The arguments startTime and stopTime can be used to check whether the model is valid within the given boundaries or to allocate memory which is necessary for storing results. Argument startTime is the fixed initial value of the independent variable[[5]](#footnote-5) [*if the independent variable is “time”, startTime is the starting time of initializaton*]. If stopTimeDefined = fmi2True, then stopTime is the defined final value of the independent variable [*if the independent variable is “time”, stopTime is the stop time of the simulation*] and if the environment tries to compute past stopTime the FMU has to return fmi2Status = fmi2Error. If stopTimeDefined = fmi2False, then no final value of the independent variable is defined and argument stopTime is meaningless. |
| fmi2Status fmi2EnterInitializationMode(fmi2Component c); | |
|  | Informs the FMU to enter Initialization Mode. Before calling this function, all variables with attribute <ScalarVariable initial = "exact" or "approx"> can be set with the “fmi2SetXXX” functions (the ScalarVariable attributes are defined in the Model Description File, see section 2.2.7). Setting other variables is not allowed. Furthermore, fmi2SetupExperiment must be called at least once before calling fmi2EnterInitializationMode, in order that startTime is defined. |
| fmi2Status fmi2ExitInitializationMode(fmi2Component c); | |
|  | Informs the FMU to exit Initialization Mode. For fmuType = fmi2ModelExchange, this function switches off all initialization equations, and the FMU enters Event Mode implicitly; that is, all continuous-time and active discrete-time equations are available. |
| fmi2Status fmi2Terminate(fmi2Component c); | |
|  | Informs the FMU that the simulation run is terminated. After calling this function, the final values of all variables can be inquired with the fmi2GetXXX(..) functions. It is not allowed to call this function after one of the functions returned with a status flag of fmi2Error or fmi2Fatal. |
| fmi2Status fmi2Reset(fmi2Component c); | |
|  | Is called by the environment to reset the FMU after a simulation run. The FMU goes into the same state as if fmi2Instantiate would have been called. All variables have their default values. Before starting a new run, fmi2SetupExperiment and fmi2EnterInitializationMode have to be called. |

### Getting and Setting Variable Values

All variable values of an FMU are identified with a variable handle called “value reference”. The handle is defined in the modelDescription.xml file (as attribute “valueReference” in element “ScalarVariable”). Element “valueReference” might not be unique for all variables. If two or more variables of the same base data type (such as fmi2Real) have the same valueReference, then they have identical values but other parts of the variable definition might be different [*(for example, min/max attributes)*].

The actual values of the variables that are defined in the modelDescription.xml file can be inquired after calling fmi2EnterInitializationMode with the following functions (restrictions for calling these functions might be present for the different FMI kinds, see below):

|  |  |
| --- | --- |
| fmi2Status fmi2GetReal (fmi2Component c, **const** fmi2ValueReference vr[],   **sizet** nvr, fmi2Real value[]);  fmi2Status fmi2GetInteger(fmi2Component c, **const** fmi2ValueReference vr[],  **sizet** nvr, fmi2Integer value[]);  fmi2Status fmi2GetBoolean(fmi2Component c, **const** fmi2ValueReference vr[],  **sizet** nvr, fmi2Boolean value[]);  fmi2Status fmi2GetString (fmi2Component c, **const** fmi2ValueReference vr[],  **sizet** nvr, fmi2String value[]); | |
|  | Get actual values of variables by providing their variable references. [*These functions are especially used to get the actual values of output variables if a model is connected with other models. Since state derivatives are also ScalarVariables, it is possible to get the value of a state derivative. This is useful when connecting FMUs together. Furthermore, the actual value of every variable defined in the modelDescription.xml file can be determined at the actually defined time instant (see section 2.2.7).*]   * Argument “vr” is a vector of “nvr” value handles that define the variables that shall be inquired. * Argument “value” is a vector with the actual values of these variables. * The strings returned by fmi2GetString must be copied in the target environment because the allocated memory for these strings might be deallocated by the next call to any of the fmi2 interface functions or it might be an internal string buffer that is reused. * Note for ModelExchange: fmi2Status = fmi2Discard is possible for fmi2GetReal only, but not for fmi2GetInteger, fmi2GetBoolean, fmi2GetString, because these are discrete-time variables and their values can only change at an event instant where fmi2Discard does not make sense. |

It is also possible to set the values of certain variables at particular instants in time using the following functions:

|  |  |
| --- | --- |
| fmi2Status fmi2SetReal (fmi2Component c, **const** fmi2ValueReference vr[],   **sizet** nvr, **const** fmi2Real value[]);  fmi2Status fmi2SetInteger(fmi2Component c, **const** fmi2ValueReference vr[],   **sizet** nvr, **const** fmi2Integer value[]);  fmi2Status fmi2SetBoolean(fmi2Component c, **const** fmi2ValueReference vr[],  **sizet** nvr, **const** fmi2Boolean value[]);  fmi2Status fmi2SetString (fmi2Component c, **const** fmi2ValueReference vr[],  **sizet** nvr, **const** fmi2String value[]); | |
|  | Set parameters, inputs, and start values, and re-initialize caching of variables that depend on these variables (see section 2.2.7 for the exact rules on which type of variables fmi2SetXXX can be called, as well as section 3.2.3 in case of ModelExchange and section 4.2.4 in case of CoSimulation).   * Argument “vr” is a vector of “nvr” value handles that define the variables that shall be set. * Argument “value” is a vector with the actual values of these variables. * All strings passed as arguments to fmi2SetString must be copied inside this function, because there is no guarantee of the lifetime of strings when this function returns. * Note: fmi2Status = fmi2Discard is possible for the fmi2SetXXX functions. |

For co-simulation FMUs, additional functions are defined in section 4.2.1 to set and inquire derivatives of variables with respect to time in order to allow interpolation.

### Getting and Setting the Complete FMU State

The FMU has an internal state consisting of all values that are needed to continue a simulation. This internal state consists especially of the values of the continuous-time states, iteration variables, parameter values, input values, delay buffers, file identifiers, and FMU internal status information. With the functions of this section, the internal FMU state can be copied and the pointer to this copy is returned to the environment. The FMU state copy can be set as actual FMU state, in order to continue the simulation from it.

[*Examples for using this feature:*

*For variable step-size control of co-simulation master algorithms (get the FMU state for every accepted communication step; if the follow-up step is not accepted, restart co-simulation from this FMU state).*

*For nonlinear Kalman filters (get the FMU state just before initialization; in every sample period, set new continuous states from the Kalman filter algorithm based on measured values; integrate to the next sample instant and inquire the predicted continuous states that are used in the Kalman filter algorithm as basis to set new continuous states).*

*For nonlinear model predictive control (get the FMU state just before initialization; in every sample period, set new continuous states from an observer, initialize and get the FMU state after initialization. From this state, perform many simulations that are restarted after the initialization with new input signals proposed by the optimizer).*]

Furthermore, the FMU state can be serialized and copied in a byte vector: [*This can be, for example, used to perform an expensive steady-state initialization, copy the received FMU state in a byte vector and store this vector on file. Whenever needed, the byte vector can be loaded from file and deserialized, and the simulation can be restarted from this FMU state, in other words, from the steady-state initialization.*]

|  |  |
| --- | --- |
| fmi2Status fmi2GetFMUstate (fmi2Component c, fmi2FMUstate\* FMUstate);  fmi2Status fmi2SetFMUstate (fmi2Component c, fmi2FMUstate FMUstate);  fmi2Status fmi2FreeFMUstate(fmi2Component c, fmi2FMUstate\* FMUstate); | |
|  | fmi2GetFMUstate makes a copy of the internal FMU state and returns a pointer to this copy (FMUstate). If on entry \*FMUstate == NULL, a new allocation is required. If \*FMUstate != NULL, then \*FMUstate points to a previously returned FMUstate that has not been modified since. In particular, fmi2FreeFMUstate had not been called with this FMUstate as an argument. [*Function fmi2GetFMUstate typically reuses the memory of this FMUstate in this case and returns the same pointer to it, but with the actual FMUstate.*]  fmi2SetFMUstate copies the content of the previously copied FMUstate back and uses it as actual new FMU state. The FMUstate copy still exists.  fmi2FreeFMUstate frees all memory and other resources allocated with the fmi2GetFMUstate call for this FMUstate. The input argument to this function is the FMUstate to be freed. If a null pointer is provided, the call is ignored. The function returns a null pointer in argument FMUstate.  These functions are only supported by the FMU, if the optional capability flag <fmiModelDescription> <ModelExchange / CoSimulation canGetAndSetFMUstate in = "true"> in the XML file is explicitly set to true (see sections 3.3.1 and 4.3.1). |
| fmi2Status fmi2SerializedFMUstateSize(fmi2Component c, fmi2FMUstate FMUstate,  size\_t \*size);  fmi2Status fmi2SerializeFMUstate (fmi2Component c, fmi2FMUstate FMUstate,  fmi2Byte serializedState[], size\_t size);  fmi2Status fmi2DeSerializeFMUstate (fmi2Component c,  **const** fmi2Byte serializedState[],  size\_t size, fmi2FMUstate\* FMUstate); | |
|  | fmi2SerializedFMUstateSize returns the size of the byte vector, in order that FMUstate can be stored in it. With this information, the environment has to allocate an fmi2Byte vector of the required length size.  fmi2SerializeFMUstate serializes the data which is referenced by pointer FMUstate and copies this data in to the byte vector serializedState of length size, that must be provided by the environment.  fmi2DeSerializeFMUstate deserializes the byte vector serializedState of length size, constructs a copy of the FMU state and returns FMUstate, the pointer to this copy. [*The simulation is restarted at this state, when calling* fmi2SetFMUState *with* FMUstate*.*]  These functions are only supported by the FMU, if the optional capability flags canGetAndSetFMUstate and canSerializeFMUstate in <fmiModelDescription><ModelExchange / CoSimulation> in the XML file are explicitly set to true (see sections 3.3.1 and 4.3.1). |

### Getting Partial Derivatives

It is optionally possible to provide evaluation of partial derivatives for an FMU. For Model Exchange, this means computing the partial derivatives at a particular time instant. For Co‑Simulation, this means to compute the partial derivatives at a particular communication point. One function is provided to compute directional derivatives. This function can be used to construct the desired partial derivative matrices.

|  |  |
| --- | --- |
| fmi2Status fmi2GetDirectionalDerivative(fmi2Component c,  **const** fmi2ValueReference vUnknown\_ref[], **size\_t** nUnknown,  **const** fmi2ValueReference vKnown\_ref[] , **size\_t** nKnown,  **const** fmi2Real dvKnown[],  fmi2Real dvUnknown[]) | |
|  | This function computes the directional derivatives of an FMU. An FMU has different Modes and in every Mode an FMU might be described by different equations and different unknowns. The precise definitions are given in the mathematical descriptions of Model Exchange (section 3.1) and Co-Simulation (section 4.1). In every Mode, the general form of the FMU equations are:  ,  where   * is the vector of unknown Real variables computed in the actual Mode:   + *Initialization Mode*: The exposed unknowns listed under <ModelStructure><InitialUnknowns> that have type Real.   + *Continuous-Time Mode* (ModelExchange):The continuous-time outputs and state derivatives (= the variables listed under <ModelStructure><Outputs> with type Real and variability = ″continuous″ and the variables listed as state derivatives under <ModelStructure><Derivatives>).   + *Event Mode (ModelExchange):* The same variables as in the *Continuous-Time Mode* and additionally variables under <ModelStructure><Outputs> with type Real and variability = ″discrete″.   + *Step Mode (CoSimulation):* The variables listed under <ModelStructure><Outputs> with type Real and variability = ″continuous″ or ″discrete″*.* If <ModelStructure><Derivatives>is present, also the variables listed here as state derivatives. * is the vector of Real input variables of function **h** that changes its value in the actual Mode. Details are described in the description of element dependencies on page 63 [*for example, continuous-time inputs in Continuous-Time Mode*. *If a variable with causality = ″independent″ is explicitely defined under ScalarVariables, a directional derivative with respect to this variable can be computed. If such a variable is not defined, the directional derivative with respect to the independent variable cannot be calculated*]. * is the set of input variables of function **h** that either changes its value in the actual Mode but are non-Real variables, or do not change their values in this Mode, but change their values in other Modes [*for example, discrete-time inputs in Continuous-Time Mode*].   If the capability attribute “providesDirectionalDerivative” is true, fmi2GetDirectionalDerivative computes a linear combination of the partial derivatives of **h** with respect to the selected input variables :  Accordingly, it computes the directional derivative vector (dvUnknown) from the seed vector (dvKnown).  [*The variable relationships are different in different modes. For example, during Continuous-Time Mode, a continuous-time output y does not depend on discrete-time inputs (because they are held constant between events). However, at Event Mode, y depends on discrete-time inputs.*]  *The function may compute the directional derivatives by numerical differentiation taking into account the sparseness of the equation system, or (preferred) by analytic derivatives.*  *Example:*  *Assume an FMU has the output equations*  *and this FMU is connected, so that appear in an algebraic loop. Then the nonlinear solver needs a Jacobian and this Jacobian can be computed (without numerical differentiation) provided the partial derivative of with respect to and is available. Depending on the environment where the FMUs are connected, these derivatives can be provided*   1. *with one wrapper function around function* fmi2GetDirectionalDerivative *to compute the directional derivatives with respect to these two variables (in other words, , ), and then the environment calls this wrapper function with to compute the partial derivative with respect to and to compute the partial derivative with respect to , or* 2. *with two direct function calls of* fmi2GetDirectionalDerivative *(in other words, ; and ).*   *Note that a direct implementation of this function with analytic derivatives:*   1. *Provides the directional derivative for all input variables; so in the above example:* 2. *Initializes all seed-values to zero; so in the above example:* 3. *Computes the directional derivative with the seed-values provided in the function arguments; so in the above example:*   ] |

1. [*Note, function* fmi2GetDirectionalDerivative *can be utilized for the following purposes:*

* *Numerical integrators of stiff methods need matrix* *.*
* *If the FMU is connected with other FMUs, the partial derivatives of the state derivatives and outputs with respect to the continuous states and the inputs are needed in order to compute the Jacobian for the system of the connected FMUs.*
* *If the FMU shall be linearized, the same derivatives as in the previous item are needed.*
* *If the FMU is used as the model for an extended Kalman filter,*  and  are needed.

1. *If a dense matrix shall be computed, the columns of the matrix can be easily constructed by successive calls of* fmi2GetDirectionalDerivative*. For example, constructing the system Jacobian*  *as dense matrix can be performed in the following way (in pseudocode notation):*

|  |
| --- |
| m = M\_fmi2Instantiate("m", ...) // "m" is the instance name  // "M\_" is the MODEL\_IDENTIFIER  // from XML file  nx = ... // number of states  x\_ref [..] = ... // vector of value references of cont.-time states  xd\_ref[..] = ... // vector of value references of state derivatives  dvKnown[1] = {1.0}; //seed vector for fmi2GetDirectionalDerivative  ...  // If required at this step, compute the Jacobian as dense matrix  // Set time, states and inputs  M\_fmi2SetTime(m, time)  M\_fmi2SetContinuousStates(m, x, nx)  M\_fmi2SetReal/Integer/Boolean/String(m, ...)  // Construct the Jacobian elements J[:,:] columnwise  **for** i **in** 1:nx **loop**  M\_fmi2GetDirectionalDerivative(m, xd\_ref, nx, x\_ref[i], 1, dvKnown, ci); J[:,i] = ci; // ci is an auxiliary vector of nx elements  // (it holds the i-th column of the Jacobian)  **end for**; |

*If the sparsity of a matrix shall be taken into account, then the matrix can be constructed in the following way:*

* *The incidence information of the matrix (whether an element is zero or not zero) is extracted from the xml file from element <ModelStructure>.*
* *A so-called graph coloring algorithm is employed to determine the columns of the matrix that can be computed by one call of* fmi2GetDirectionalDerivative*. Efficient graph coloring algorithms are freely available, such as library ColPack (*[*http://www.cscapes.org/coloringpage/*](http://www.cscapes.org/coloringpage/)*) written in C/C++ (LGPL), or the routines by Coleman, Garbow, Moré: “Software for estimating sparse Jacobian matrices”, ACM Transactions on Mathematical Software - TOMS , vol. 10, no. 3, pp. 346-347, 1984. See e.g.* [*http://www.netlib.org/toms/618*](http://www.netlib.org/toms/618)*.*
* *For the columns determined in (2), one call to* fmi2DirectionalDerivative *is made. After each such call, the elements of the resulting directional derivative vector are copied into their correct locations of the partial derivative matrix.*

*More details and implementational notes are available from (Akesson et.al. 2012).*

]

## FMI Description Schema

All static information related to an FMU is stored in the text file modelDescription.xml in XML format. Especially, the FMU variables and their attributes such as name, unit, default initial value, etc. are stored in this file. The structure of this XML file is defined with the schema file “fmiModelDescription.xsd”. This schema file utilizes the following helper schema files:

fmi2Annotation.xsd  
fmi2AttributeGroups.xsd

fmi2ScalarVariable.xsd

fmi2Type.xsd  
fmi2VariableDependency.xsd  
fmi2Unit.xsd

In this section these schema files are discussed. The normative definition are the above mentioned schema files[[6]](#footnote-6). Below, optional elements are marked with a “dashed” box. The required data types (like: xs:normalizedString) are defined in the XML-schema standard: [http://www.w3.org/TR/XMLschema-2/](http://www.w3.org/TR/xmlschema-2/). The types used in the fmi2 schema files are:

|  |  |  |
| --- | --- | --- |
| *XML* | Description ([http://www.w3.org/TR/XMLschema-2/](http://www.w3.org/TR/xmlschema-2/)) | *Mapping to C* |
| xs:double | IEEE double-precision 64-bit floating point type  [*In order to not loose precision, a number of this type should be stored on an XML file with at least* ***16*** *significant digits; for example 2/3 should be stored as*  *0.6666666666666667*] | double |
| xs:int | Integer number with maximum value 2147483647 and minimum value -2147483648 (32 bit Integer) | int |
| xs:unsignedInt | Integer number with maximum value 4294967295 and minimum value 0 (unsigned 32 bit Integer) | unsigned int |
| xs:boolean | Boolean number. Legal literals: false, true, 0, 1 | char |
| xs:string | Any number of characters | char\* |
| xs:normalizedString | String without carriage return, line feed, and tab characters | char\* |
| xs:dateTime | Date, time and time zone (for details see the link above). Example: 2002-10-23T12:00:00Z (noon on October 23, 2002, Greenwich Mean Time) | tool specific |

The first line of an XML file, such as modelDescription.xml, must contain the encoding scheme of the XML file. It is required that the encoding scheme is always UTF-8:

<?xml version="1.0" encoding="UTF-8"?>

The FMI schema files (\*.xsd) are also stored in “UTF-8”.   
[*Note that the definition of an encoding scheme is a prerequisite in order for the XML file to contain letters outside of the 7 bit ANSI ASCII character set, such as German umlauts, or Asian characters. Furthermore, note the FMI calling interface requires that strings are encoded in UTF-8. Since the \*.xml files are also required to be encoded in UTF-8, string variables need not to be transformed when reading from the xml-files in to C string variables.*]

The special values NAN, INF, +INF, and -INF for variables values are not allowed in the FMI xml files.

Note that child information items, such as “elements” in a “sequence” are **ordered lists** according to document order, whereas attribute information items are **unordered sets** (see [http://www.w3.org/TR/XML-infoset/#infoitem.element](http://www.w3.org/TR/xml-infoset/#infoitem.element)). The FMI schema is based on ordered lists in a sequence and therefore parsing must preserve this order. [*For example, the information stored in* ModelVariables.Derivatives *is only correct if this property is fulfilled.*]

### Definition of an FMU (fmiModelDescription)

This is the root-level schema file and contains the following definition (the figure below contains all elements in the schema file. Data is defined by attributes to these elements):



On the top level, the schema consists of the following elements (see figure above[[7]](#footnote-7)):

|  |  |
| --- | --- |
| *Element-Name* | *Description* |
| ModelExchange | If present, the FMU is based on “FMI for Model Exchange” [*(in other words, the FMU includes the model or the communication to a tool that provides the model, and the environment provides the simulation engine)*]. |
| CoSimulation | If present, the FMU is based on “FMI for Co-Simulation” [*(in other words, the FMU includes the model and the simulation engine, or a communication to a tool that provides the model and the simulation engine, and the environment provides the master algorithm to run coupled FMU co-simulation slaves together)*]. |
| UnitDefinitions | A global list of unit and display unit definitions [*for example, to convert display units into the units used in the model equations*]. These definitions are used in the XML element “ModelVariables”. |
| TypeDefinitions | A global list of type definitions that are utilized in “ModelVariables”. |
| LogCategories | A global list of log categories that can be set to define the log information that is supported from the FMU. |
| DefaultExperiment | Providing default settings for the integrator, such as stop time and relative tolerance. |
| VendorAnnotations | Additional data that a vendor might want to store and that other vendors might ignore. |
| ModelVariables | The central FMU data structure defining all variables of the FMU that are visible/accessible via the FMU functions. |
| ModelStructure | Defines the structure of the model. Especially, the ordered lists of outputs, continuous-time states and initial unknowns (the unknowns during Initialization Mode) are defined here. For more details on ModelStructure, see section 2.2.8. Furthermore, the dependency of the unkowns from the knowns can be optionally defined. [*This information can be, for example, used to compute efficiently a sparse Jacobian for simulation, or to utilize the input/output dependency in order to detect that in some cases there are actually no algebraic loops when connecting FMUs together.*] |

At least one element of ModelExchange or CoSimulation must be present to identify the type of the FMU. If both elements are defined, different types of models are included in the FMU. The details of these elements are defined in section 3.3.1 and section 4.3.1.

The XML attributes of fmiModelDescription are:



Version of FMI (Clarification for FMI 2.0.1: for FMI 2.0.x revisions fmiVersion is defined as “2.0”)

|  |  |
| --- | --- |
| *Attribute-Name* | *Description* |
| fmiVersion | Version of “FMI for Model Exchange or Co-Simulation” that was used to generate the XML file. The value for this version is “2.0”.  [*Clarification for FMI 2.0.1: The version string for FMUs generated according to FMI 2.0.1 shall be “2.0” to be compatible with FMI 2.0 importers.*] |
| modelName | The name of the model as used in the modeling environment that generated the XML file, such as “Modelica.Mechanics.Rotational.Examples.CoupledClutches”. |
| guid | The “Globally Unique IDentifier” is a string that is used to check that the XML file is compatible with the C functions of the FMU. Typically, when generating the XML file, a fingerprint of the “relevant” information is stored as guid and in the generated C-function. |
| description | Optional string with a brief description of the model. |
| author | Optional string with the name and organization of the model author. |
| version | Optional version of the model, for example “1.0”. |
| copyright | Optional information on the intellectual property copyright for this FMU. [*Example: copyright = “© My Company 2011”*]. |
| license | Optional information on the intellectual property licensing for this FMU. [*Example: license = “BSD license <license text or link to license>”*]. |
| generationTool | Optional name of the tool that generated the XML file. |
| generationDateAndTime | Optional date and time when the XML file was generated. The format is a subset of “xs:dateTime” and should be: “YYYY-MM-DDThh:mm:ssZ" (with one “T” between date and time; “Z” characterizes the Zulu time zone, in other words Greenwich meantime).  [*Example: "2009-12-08T14:33:22Z"*]. |
| variableNamingConvention | Defines whether the variable names in “ModelVariables / ScalarVariable / name” and in “TypeDefinitions / Type / name” follow a particular convention. For the details, see section 2.2.9. Currently standardized are:   * “*flat*”: A list of strings (the default). * “structured“: Hierarchical names with “.” as hierarchy separator, and with array elements and derivative characterization. |
| numberOfEventIndicators | The (fixed) number of event indicators for an FMU based on FMI for Model Exchange.  For Co-Simulation, this value is ignored. |

[*The* *attribute “numberOfContinuousStates” available in FMI 1.0 has been removed for FMI 2.0, since this information can be deduced from the remaining data in the XML file.*]

### Definition of Units (UnitDefinitions)

[*In this section, the units of the variables are (optionally) defined. Unit support is important for technical systems since otherwise it is very easy for errors to occur. Unit handling is a difficult topic, and there seems to be no method available that is really satisfactory for all applications, such as unit check, unit conversion, unit propagation or dimensional analysis. In FMI, a pragmatic approach is used that takes into account that every software system supporting units has potentially its own specific technique to describe and utilize units. The approach used here is slightly different than FMI 1.0 to reduce the need for standardized string representations.*]

Element “**UnitDefinitions**” of fmiModelDescription is defined as:



It consists of zero or more Unit definitions[[8]](#footnote-8). A Unit is defined by its name attribute such as “N.m” or “N\*m” or “Nm”, which must be unique with respect to all other defined elements of the UnitDefinitions list. If a variable is associated with a Unit, then the value of the variable has to be provided with the fmi2SetXXX functions and is returned by the fmi2GetXXX functions with respect to this Unit. [*The purpose of the name is to uniquely identify a unit and, for example, use it to display the unit in menus or in plots. Since there is no standard to represent units in strings, and there are different ways how this is performed in different tools, no specific string representation of the unit is required.*]

Optionally, a value given in unit Unit can be converted to a value with respect to unit BaseUnit utilizing the conversion factor and offset attributes:



Besides factor and offset, the BaseUnit definition consists of the exponents of the 7 SI base units “kg”, “m”, “s”, “A”, “K”, “mol”, “cd”, and of the exponent of the SI derived unit “rad”. [*Depending on the analysis/operation carried out, the SI derived unit “rad” is or is not utilized, see discussion below. The additional “rad” base unit helps to handle the often occurring quantities in technical systems that depend on an angle.*]

A value with respect to Unit (abbreviated as “Unit\_value”) is converted with respect to BaseUnit (abbreviated as “BaseUnit\_value”) by the equation:

BaseUnit\_value = factor\*Unit\_value + (if relativeQuantity then 0 else offset)

where factor and offset are attributes of the BaseUnit, and relativeQuantity an attribute of the TypeDefinition of a variable.

[*For example, if pbar is a pressure value in Unit “bar”, and pPa is the pressure value in BaseUnit, then*

*pPa = 105 pbar*

*and therefore,* factor = 1.0e5 *and* offset = 0.0.

*In the following table several unit examples are given (Note that if in column “*exponents*” the definition “kgm2/s2“is present, then the attributes of* BaseUnit *are: “*kg=1, m=2, s=-2*”.):*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***Quantity*** | **Unit.name** (examples) | **Unit.BaseUnit** | | |
| **exponents** | **factor** | **offset** |
| *Torque* | "N.m" |  | 1.0 | 0.0 |
| *Energy* | "J" |  | 1.0 | 0.0 |
| *Pressure* | "bar" |  | 1.0e5 | 0.0 |
| *Angle* | "deg" | rad | 0.01745329251994330 (= pi/180) | 0.0 |
| *Angular velocity* | "rad/s" | rad/s | 1.0 | 0.0 |
| *Angular velocity* | "rpm" | rad/s | 0.1047197551196598 (=2\*pi/60) | 0.0 |
| *Frequency* | "Hz" | rad/s | 6.283185307179586 (= 2\*pi) | 0.0 |
| *Temperature* | "oF" | K | 0.5555555555555556 (= 5/9) | 255.3722222222222 (= 273.15-32\*5/9) |
| *Per cent by length* | "%/m" | 1/m | 0.01 | 0.0 |
| *Parts per million* | "ppm" | 1 | 1.0e-6 | 0.0 |
| *Length* | "km" | m | 1000 | 0.0 |
| *Length* | "yd" | m | 0.9144 | 0.0 |

*Note that “Hz” is typically used as Unit.name for a frequency quantity, but it can also be used as DisplayUnit for an angular velocity quantity (since “*revolution/s*”).*

*The BaseUnit definitions can be utilized for different purposes (the following application examples are optional and a tool may also completely ignore the Unit definitions):*

***Signal connection check:***

*When two signals v1 and v2 are connected together, and on at least one of the signals no BaseUnit element is defined, then the connection equation “v2 = v1” holds (if v1 is an output of an FMU and v2 is an input of another FMU, with* fmi2GetXXX *the value of v1 is inquired and used as value for v2 by calling* fmi2SetXXX*).*

*When two signals v1 and v2 are connected together, and for both of them BaseUnit elements are defined, then they must have identical exponents of their BaseUnit. If factor and offset are also identical, again the connection equation “v2 = v1” holds. If factor and offset are not identical, the tool may either trigger an error or, if supported, perform a conversion; in other words, use the connection equation (in this case the* relativeQuantity *of the* TypeDefinition*, see below, has to be taken into account in order to determine whether* offset *shall or shall not be utilized):*

*factor(v1)\*v1 + (if relativeQuantity(v1) then 0 else offset(v1)) = factor(v2)\*v2 + (if relativeQuantity(v2) then 0 else offset(v2))*

*where relativeQuantity(v1) = relativeQuantity(v2*) is required.

*As a result, wrong connections can be detected (for example, connecting a force with an angle signal would trigger an error) and conversions between, say, US and SI units can be either automatically performed or, if not supported, an error is triggered as well. Note that this approach is not satisfactory for variables belonging to different quantities that have, however, the same* BaseUnit*, such as quantities “Energy” and “Torque”, or “AngularVelocity” and “Frequency”. To handle such cases, quantity definitions have to be taken into account (see TypeDefinitions) and quantity names need to be standardized.*

*This approach allows a general treatment of units, without being forced to standardize the grammar and allowed values for units (for example, in FMI 1.0, a unit could be defined as “N.m” in one FMU and as “N\*m” in another FMU, and a tool would have to reject a connection, since the units are not identical. In FMI 2.0, the connection would be accepted, provided both elements have the same BaseUnit definition).*

***Dimensional analysis of equations:***

*In order to check the validity of equations in a modeling language, the defined units can be used for dimensional analysis, by using the BaseUnit definition of the respective unit. For this purpose, the BaseUnit “rad” has to be treated as “1”. Example:*

*J\*α = τ → [kg.m2]\*[rad/s2] = [kg.m2/s2]). // o.k. (“rad” is treated as “1”)*

*J\*α = f → [kg.m2]\*[rad/s2] = [kg.m/s2]). // error, since dimensions do not agree*

***Unit propagation:***

*If unit definitions are missing for signals, they might be deduced from the equations where the signals are used. If no unit computation is needed, “rad” is propagated. If a unit computation is needed and one of the involved units has “rad” as a BaseUnit, then unit propagation is not possible. Examples:*

* *a = b + c, and Unit of c is provided, but not Unit of a and b:  
  The Unit definition of c (in other words Unit.name, BaseUnit*, *DisplayUnit) is also used for a and b. For example, if BaseUnit(c) = “rad/s”, then BaseUnit(a) = BaseUnit(b) = “rad/s”.*
* *a = b\*c, and Unit of a and of c is provided, but not Unit of b:  
  If “rad” is either part of the BaseUnit of “a” and/or of “c”, then the BaseUnit of b cannot be deduced (otherwise it can be deduced). Example: If BaseUnit(a)=”kg.m/s2” and BaseUnit(c)=”m/s2”, then the BaseUnit(b) can be deduced to be “kg”. In such a case Unit.name of b cannot be deduced from the Unit.name of a and c, and a tool would typically construct the Unit.name of b from the deduced BaseUnit.*

]

Additionally to the unit definition, optionally a set of display units can be defined that can be utilized for input/output of a value:



A DisplayUnit is defined by name, factor and offset. The attribute name must be unique with respect to all other names of the DisplayUnit definitions of the same Unit [(different Unit elements may have the same DisplayUnit names)]. A value with respect to Unit (abbreviated as “Unit\_value”) is converted with respect to DisplayUnit (abbreviated as “DisplayUnit\_value”) by the equation:

DisplayUnit\_value = factor\*Unit\_value + offset

[*“offset” is, for example, needed for temperature units.*]

[*For example, if TK is the temperature value of Unit.name (in “K”) and TF is the temperature value of DisplayUnit (in “oF”), then*

*TF = (9/5) \* (TK - 273.15 ) + 32*

*and therefore, factor = 1.8 (=9/5) and offset = -459.67 (= 32 – 273.15\*9/5).*

*Both the DisplayUnit.name definitions as well as the Unit.name definitions are used in the ScalarVariable elements. Example for a definition:*

<Unit name="rad/s">

<BaseUnit s="-1" rad="1"/>

<DisplayUnit name="deg/s" factor= "57.29577951308232"/>

<DisplayUnit name="rev/min" factor= "9.549296585513721"/>  
</Unit>

<Unit name="bar">  
 <BaseUnit kg="1", m="-1", s="-2", factor="1.0e5", offset="0"/>  
</Unit>

<Unit name="Re">  
 <BaseUnit/> // unit = "1"   
 //(dimensionless, all exponents of BaseUnit are zero)  
</Unit>

<Unit name="Euro/PersonYear"/> // no mapping to BaseUnit defined

]

The schema definition is present in a separate file “fmi2Unit.xsd”.

### Definition of Types (TypeDefinitions)

Element “**TypeDefinitions**” of fmiModelDescription is defined as:



This element consists of a set of “SimpleType” definitions according to schema “fmi2SimpleType” in file “fmi2Type.xsd”. One “SimpleType” has a type “name” and “description" as attributes. Attribute “name” must be unique with respect to all other elements of the TypeDefinitions list. Furthermore, “name” of a “SimpleType” must be different to all “name” attributes of ScalarVariables [*if the same names would be used, then this would nearly always give problems when importing the FMU in an environment such as Modelica, where a type name cannot be used as instance name*]. Additionally, one of the elements Real, Integer, Boolean, String, or Enumeration must be present. They have the following definitions:

 

[*The attributes of “Real” and “Integer” are collected in the attribute groups “fmi2RealAttributes” and “fmi2IntegerAttributes” in file “fmi2AttributeGroups.xsd”, since these attributes are reused in the ScalarVariable element definitions below.*]



These definitions are used as default values in element ScalarVariables [*in order that, say, the definition of a “Torque” type does not have to be repeated over and over again*]. The attributes and elements have the following meaning:

|  |  |
| --- | --- |
| *Name* | *Description* |
| quantity | Physical quantity of the variable, for example “Angle”, or “Energy”. The quantity names are not standardized. |
| unit | Unit of the variable defined with UnitDefinitions.Unit.name that is used for the model equations. [*For example, "N.m": in this case a Unit.name = "N.m" must be present under UnitDefinitions.*  *Note that for variables that are without a unit, the element should not have a unit attribute.*  *Giving an empty string as a unit attribute specifies a valid unit that needs to be defined among the unit definitions.*] |
| displayUnit | Default display unit. The conversion to the “unit” is defined with the element “<fmiModelDescription><UnitDefinitions>”. If the corresponding “displayUnit” is not defined under <UnitDefinitions> <Unit> <DisplayUnit>, then displayUnit is ignored. It is an error if displayUnit is defined in element Real, but unit is not, or unit is not defined under <UnitDefinitions><Unit>. |
| relativeQuantity | If this attribute is true, then the “offset” of “baseUnit” and “displayUnit” must be ignored (for example, 10 degree Celsius = 10 Kelvin if “relativeQuantity = true” and not 283.15 Kelvin). |
| min | Minimum value of variable (variable Value ≥ min). If not defined, the minimum is the largest negative number that can be represented on the machine. The min definition is information from the FMU to the environment defining the region in which the FMU is designed to operate, see also comment after this table. |
| max | Maximum value of variable (variableValue ≤ max). If not defined, the maximum is the largest positive number that can be represented on the machine. The max definition is information from the FMU to the environment defining the region in which the FMU is designed to operate, see also comment after this table. |
| nominal | Nominal value of variable. If not defined and no other information about the nominal value is available, then nominal = 1 is assumed. [*The nominal value of a variable can be, for example, used to determine the absolute tolerance for this variable as needed by numerical algorithms:  absoluteTolerance =* nominal*\**tolerance*\*0.01*  *where* tolerance *is, for example, the relative tolerance defined in <DefaultExperiment>, see section 2.2.5.*] |
| unbounded | If true, indicates that during time integration, the variable gets a value much larger than its nominal value nominal. [*Typical examples are the monotonically increasing rotation angles of crank shafts and the longitudinal position of a vehicle along the track in long distance simulations. This information can, for example, be used to increase numerical stability and accuracy by setting the corresponding bound for the relative error to zero (relative tolerance = 0.0), if the corresponding variable or an alias of it is a continuous state variable.*] |
| Item | Item of an enumeration has a sequence of “name” and “value” pairs. The values can be any integer number but must be unique within the same enumeration (in order that the mapping between “name” and “value” is bijective). An Enumeration element must have at least one Item. |

[A*ttributes* “*min” and* “*max” can be set for variables of type Real, Integer or Enumeration. The question is how fmi2SetReal, fmi2SetInteger, fmi2GetReal, fmi2GetInteger shall utilize this definition. There are several conflicting requirements:*

* *Avoiding forbidden regions (for example, if “u” is an input and “sqrt(u)” is computed in the FMU, min=0 on “u” shall guarantee that only values of “u” in the allowed regions are provided).*

*Numerical algorithms (ODE-solver, optimizers. nonlinear solvers) do not guarantee constraints. If a variable is outside of the bounds, the solver tries to bring it back into the bounds. As a consequence, calling* fmi2GetReal *during an iteration of such a solver might return values that are not in the defined min/max region. After the iteration is finalized, it is only guaranteed that a value is within its bounds up to a certain numerical precision.*

* *In debug mode checks on min/max should be performed. For maximum performance on a real-time system the checks might not be performed.*

*The approach in FMI is therefore that min/max definitions are information from the FMU to the environment defining the region in which the FMU is designed to operate. The environment is free to utilize this information (typically, in debug mode of the environment the min/max is checked in the cases as stated above). In any case, it is expected that the FMU handles variables appropriately where the region definition is critical. For example, dividing by an input (so the input should not be in a small range of zero) or taking the square root of an input (so the input should not be negative) may either result in* fmi2Error*, or the FMU is able to handle this situation in other ways.*

*If the FMU is generated so that min/max shall be checked whenever meaningful (for example, for debug purposes), then the following strategy should be used:*

*If* fmi2SetReal *or* fmi2SetInteger *is called violating the min/max attribute settings of the corresponding variable, the following actions are performed:*

* *On a fixed or tunable parameter,* fmi2Status = fmi2Discard *is returned.*
* *On an input, the FMU decides what to return (If no computation is possible, it could return* fmi2Status = fmi2Discard*, in other situations it may return* fmi2Warning *or* fmi2Error*, or* fmi2OK*, if it is uncritical).*

*If an FMU defines min/max values for Integer and Enumerations (local and output variables), then the expected behavior of the FMU is that fmi2GetInteger returns values in the defined range.*

*If an FMU defines min/max values for Reals, then the expected behavior of the FMU is that fmi2GetReal returns values at the solution (accepted steps of the integrators) in the defined range with a certain uncertainty related to the tolerances of the numerical algorithms.*]

### Definition of Log Categories (LogCategories)

Element “**LogCategories**” of “fmiModelDescription is defined as:



LogCategories defines an unordered set of category strings that can be utilized to define the log output via function “logger”, see section 2.1.5. A tool is free to use any normalizedString for a category value. The “name” attribute of “Category” must be unique with respect to all other elements of the LogCategories list.

There are the following standardized names for “Category” and these names should be used if a tool supports the corresponding log category. If a tool supports one of these log categories and wants to expose it, then an element Category with this name should be added to LogCategories [*To be clear, only the Category names listed under LogCategories in the xml-file are known to the environment in which the FMU is called.*]

|  |  |
| --- | --- |
| *Category name* | *Description* |
| logEvents | Log all events (during initialization and simulation). |
| logSingularLinearSystems | Log the solution of linear systems of equations if the solution is singular (and the tool picked one solution of the infinitely many solutions). |
| logNonlinearSystems | Log the solution of nonlinear systems of equations. |
| logDynamicStateSelection | Log the dynamic selection of states. |
| logStatusWarning | Log messages when returning fmi2Warning status from any function. |
| logStatusDiscard | Log messages when returning fmi2Discard status from any function. |
| logStatusError | Log messages when returning fmi2Error status from any function. |
| logStatusFatal | Log messages when returning fmi2Fatal status from any function. |
| logStatusPending | Log messages when returning fmi2Pending status from any function. |
| logAll | Log all messages. |

The optional attribute description shall contain a description of the respective log category. [*Typically, this string can be shown by a tool if more details for a log category shall be presented.*]

[*This approach to define LogCategories has the following advantages:*

1. *A simulation environment can present the possible log categories in a menu and the user can select the desired one (in the FMI 1.0 approach, there was no easy way for a user to figure out from a given FMU what log categories could be provided). Note that since element* <LogCategories> *is optional, an FMU does not need to expose its log categories.*
2. *The log output is drastically reduced, because via* fmi2SetDebugLogging *exactly the categories are set that shall be logged and therefore the FMU only has to print the messages with the corresponding categories to the* logger *function. In FMI 1.0, it was necessary to provide all log output of the FMU to the* logger *and then a filter in the* logger *could select what to show to the end-user. The approach introduced in FMI 2.0 is therefore much more efficient.*

]

### Definition of a Default Experiment (DefaultExperiment)

Element “**DefaultExperiment**” of fmiModelDescription is defined as:



DefaultExperiment consists of the optional default start time, stop time, relative tolerance, and step size for the first simulation run. A tool may ignore this information. However, it is convenient for a user that startTime, stopTime, tolerance and stepSize have already a meaningful default value for the model at hand. Furthermore, for CoSimulation the stepSize defines the preferred communicationStepSize.

### Definition of Vendor Annotations (VendorAnnotations)

Element “**VendorAnnotations**” of fmiModelDescription is defined as:



VendorAnnotations consist of an ordered set of annotations that are identified by the name of the tool that can interpret the “any” element. The “any” element can be an arbitrary XML data structure defined by the tool. Attribute “name” must be unique with respect to all other elements of the VendorAnnotation list.

### Definition of Model Variables (ModelVariables)

The “**ModelVariables**” element of fmiModelDescription is the central part of the model description. It provides the static information of all exposed variables and is defined as:



The “ModelVariables” element consists of an ordered set of “ScalarVariable” elements (see figure above). The first element has index = 1, the second index=2, etc. This ScalarVariable index is used in element ModelStructure to uniquely and efficiently refer to ScalarVariable definitions. A “ScalarVariable” represents a variable of primitive type, like a real or integer variable. For simplicity, only scalar variables are supported in the schema file in this version and structured entities (like arrays or records) have to be mapped to scalars. The schema definition is present in a separate file “fmi2ScalarVariable.xsd”.

The attributes of “ScalarVariable” are:



|  |  |
| --- | --- |
| *Attribute-Name* | *Description* |
| name | The full, unique name of the variable. Every variable is uniquely identified within an FMU instance by this name or by its ScalarVariable index (the element position in the ModelVariables list; the first list element has index=1). |
| valueReference | A handle of the variable to efficiently identify the variable value in the model interface. This handle is a secret of the tool that generated the C functions; it is not required to be unique. The only guarantee is that valueReference is sufficient to identify the respective variable value in the call of the C functions. This implies that it is unique for a particular base data type (Real, Integer/Enumeration, Boolean, String) with exception of variables that have identical values (such variables are also called “alias” variables). This attribute is “required”. |
| description | An optional description string describing the meaning of the variable. |
| causality | Enumeration that defines the causality of the variable. Allowed values of this enumeration:   * "parameter": Independent parameter (a data value that is constant during the simulation and is provided by the environment and cannot be used in connections). variability must be "fixed" or "tunable". initial must be exact or not present (meaning exact). * "calculatedParameter": A data value that is constant during the simulation and is computed during initialization or when tunable parameters change. variability must be "fixed" or "tunable". initial must be "approx", "calculated" or not present (meaning calculated). * "input": The variable value can be provided from another model or slave. It is not allowed to define initial. * "output": The variable value can be used by another model or slave. The algebraic relationship to the inputs is defined via the dependencies attribute of <fmiModelDescription><ModelStructure><Outputs><Unknown>. * "local": Local variable that is calculated from other variables or is a continuous-time state (see section 2.2.8). It is not allowed to use the variable value in another model or slave. * "independent": The independent variable (usually “time”). All variables are a function of this independent variable. variability must be "continuous". At most one ScalarVariable of an FMU can be defined as "independent". If no variable is defined as "independent", it is implicitly present with name = "time" and unit = "s". If one variable is defined as "independent", it must be defined as "Real" without a "start" attribute. It is not allowed to call function fmi2SetReal on an "independent" variable. Instead, its value is initialized with fmi2SetupExperiment and after initialization set by fmi2SetTime for ModelExchange and by arguments currentCommunicationPoint and communicationStepSize of fmi2DoStep for CoSimulation. [*The actual value can be inquired with fmi2GetReal.*]   The default of causality is “local”. A continuous-time state must have causality = "local" or "output", see also section 2.2.8.  [*causality = "calculatedParameter" and causality = "local" with variability = "fixed" or "tunable" are similar. The difference is that a calculatedParameter can be used in another model or slave, whereas a local variable cannot. For example, when importing an FMU in a Modelica environment, a "calculatedParameter" should be imported in a* public *section as* final parameter*, whereas a "local" variable should be imported in a* protected *section of the model.*] |
| variability | * Enumeration that defines the time dependency of the variable, in other words, it defines the time instants when a variable can change its value. [*The purpose of this attribute is to define when a result value needs to be inquired and to be stored. For example, discrete variables change their values only at event instants (ModelExchange) or at a communication point (CoSimulation) and it is therefore only necessary to inquire them with* fmi2GetXXX *and store them at event times*]. Allowed values of this enumeration: * "constant": The value of the variable never changes. * "fixed": The value of the variable is fixed after initialization, in other words, after fmi2ExitInitializationMode was called the variable value does not change anymore. * "tunable": The value of the variable is constant between *external events* (ModelExchange) and between *Communication Points* (Co-Simulation) due to changing variables with causality = "parameter" or "input" and variability = "tunable". Whenever a parameter or input signal with variability = "tunable" changes, an event is triggered externally (ModelExchange), or the change is performed at the next *Communication Point* (Co-Simulation) and the variables with variability = "tunable" and causality = "calculatedParameter" or "output" must be newly computed. * "discrete": ModelExchange: The value of the variable is constant between *external* and *internal events* (= time, state, step events defined implicitly in the FMU). Co-Simulation: By convention, the variable is from a “real” sampled data system and its value is only changed at Communication Points (also inside the slave). * "continuous": Only a variable of type = “Real” can be “continuous”.  ModelExchange: No restrictions on value changes. Co-Simulation: By convention, the variable is from a differential   The default is “continuous”.  [*Note that the information about continuous states is defined with element* fmiModelDescription.ModelStructure.Derivatives] |
| initial | Enumeration that defines how the variable is initialized. It is not allowed to provide a value for initial if causality = "input" or "independent":   * = "exact": The variable is initialized with the start value (provided under Real, Integer, Boolean, String or Enumeration). * = "approx": The variable is an iteration variable of an algebraic loop and the iteration at initialization starts with the start value. * = "calculated": The variable is calculated from other variables during initialization. It is not allowed to provide a “start” value.   If initial is not present, it is defined by the table below based on causality and variability. If initial = exact or approx, or causality = ″input″, a start value must be provided. If initial = calculated, or causality = ″independent″, it is not allowed to provide a start value.  [*The environment decides when to use the start value of a variable with causality = ″input″. Examples: (a) automatic tests of FMUs are performed, and the FMU is tested by providing the start value as constant input. (b) For a ModelExchange FMU, the FMU might be part of an algebraic loop. If the input variable is iteration variable of this algebraic loop, then initialization starts with its start value.*].  If fmiSetXXX is not called on a variable with causality = ″input″, then the FMU must use the start value as value of this input. |
| canHandleMultipleSetPerTimeInstant | |
|  | Only for ModelExchange (if only CoSimulation FMU, this attribute must not be present. If both ModelExchange and CoSimulation FMU, this attribute is ignored for CoSimulation):  Only for variables with variability = "input":  If present with value = false then only one fmi2SetXXX call is allowed at one super dense time instant (model evaluation) on this variable. That is, this input is not allowed to appear in a (real) algebraic loop requiring multiple calls of fmi2SetXXX on this variable [*for example, due to a Newton iteration*].  [*This flag must be set by FMUs where (internal) discrete-time states are directly updated when assigned (xd := f(xd) instead of xd = f(previous(xd)), and at least one output depends on this input and on discrete states.   It is strongly recommended that such an FMU checks the fulfillment of the requirement by itself during run-time, because an environment might not be able to check it; usually, there is a generic mechanism to import an FMU in an environment, but the mechanism to connect FMUs together is unrelated to the import mechanism. For example, there is no mechanism in the Modelica language to formulate connection restrictions for C-functions (the FMU) called in a Modelica model.*] |

**fmi2SetXXX** can be called on any variable with variability ≠ "constant" **before initialization** (before calling fmi2EnterInitializationMode)

* if initial = "exact" or "approx" [*in order to set the corresponding* start *value*].  
  [Note that this prevents any changes to the input before fmi2EnterInitializationMode is called.]

**fmi2SetXXX** can be called on any variable with variability ≠ "constant" **during initialization** (after calling fmi2EnterInitializationMode and before fmi2ExitInitializationMode is called)

* if initial = "exact" [*in order to set the corresponding* start *value*], or
* if causality = "input" [*in order to provide new values for inputs*]

**fmi2SetXXX** can be called on any variable **for ModelExchange** **at an event instant** (after calling fmi2EnterEventMode and before fmi2EnterContinuousTimeMode is called), and **for Co-Simulation at every communication point**,

* if causality = "parameter" and variability = "tunable" [*in order to change the value of the tunable parameter at an event instant or at a communication point*], or
* if causality = "input" [*in order to provide new values for inputs*]

**fmi2SetXXX** can be called on any variable for **ModelExchange in Continuous-Time Mode**

* if causality = "input" and variability = "continuous"   
  [*in order to provide new values for inputs during continuous integration*]

If initial is not present, its value is defined by the following tables based on the values of causality and variability:

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **causality** | | | | | |
|  |  |  | **parameter** | **calculatedparameter** | **input** | **output** | **local** | **independent** |
| **variability** | data | **constant** | -- | -- | -- | (A) | (A) | -- |
| **fixed** | (A) | (B) | -- | -- | (B) | -- |
| **tunable** | (A) | (B) | -- | -- | (B) | -- |
| signals | **discrete** | -- | -- | (D) | (C) | (C) | -- |
| **continuous** | -- | -- | (D) | (C) | (C) | (E) |

with

|  |  |  |
| --- | --- | --- |
|  | **initial** | |
|  | **default** | **possible values** |
| (A) | exact | exact |
| (B) | calculated | approx,  calculated |
| (C) | calculated | exact,  approx,  calculated |
| (D) | --- | --- |
| (E) | --- | --- |

[*Note: (1) If causality = "independent", it is neither allowed to define a value for initial nor a value for start. (2) If causality = "input", it is not allowed to define a value for* initial *and a value for* start *must be defined. (3) If (C) and initial = "exact", then the variable is explicitly defined by its start value in Initialization Mode (so directly after calling* fmi2ExitInitializationMode*, the value of the variable is either the start value stored in element* <ScalarVariable><*XXX* start*=YYY/*> *or the value provided by* fmiSetXXX*, if this function was called on this variable).*]

The following combinations of variability/causality settings are allowed:

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **causality** | | | | | |
|  |  |  | **parameter** | **calculated Parameter** | **input** | **output** | **local** | **independent** |
| **variability** | data | **constant** | -- (a) | -- (a) | -- (a) | (7) | (10) | -- (c) |
| **fixed** | (1) | (3) | -- (d) | -- (e) | (11) | -- (c) |
| **tunable** | (2) | (4) | -- (d) | -- (e) | (12) | -- (c) |
| signals | **discrete** | -- (b) | -- (b) | (5) | (8) | (13) | -- (c) |
| **continuous** | -- (b) | -- (b) | (6) | (9) | (14) | (15) |

[*Discussion of the combinations that are not allowed:*

|  |  |
| --- | --- |
|  | *Explanation why this combination is not allowed* |
| *(a)* | *The combinations “constant / parameter”, “constant / calculatedParameter” and “constant / input” do not make sense, since parameters and inputs are set from the environment, whereas a constant has always a value.* |
| *(b)* | *The combinations “discrete / parameter”, “discrete / calculatedParameter”, “continuous / parameter” and continuous / calculatedParameter do not make sense, since causality = “parameter” and “calculatedParameter” define variables that do not depend on time, whereas “discrete” and “continuous” define variables where the values can change during simulation.* |
| *(c)* | *For an “independent” variable only variability = “continuous” makes sense.* |
| *(d)* | *A fixed or tunable “input” has exactly the same properties as a fixed or tunable parameter. For simplicity, only fixed and tunable parameters shall be defined.* |
| *(e)* | *A fixed or tunable “output” has exactly the same properties as a fixed or tunable calculatedParameter. For simplicity, only fixed and tunable calculatedParameters shall be defined.* |

*Discussion of the combinations that are allowed:*

|  |  |  |
| --- | --- | --- |
|  | ***Setting*** | ***Example*** |
| *(1)* | *fixed parameter* | *Non-tunable independent parameter* |
| *(2)* | *tunable parameter* | *Tunable independent parameter (changing such a parameter triggers an external event (ModelExchange) or takes effect at the next Communication Point (CoSimulation), and tunable calculatedParameter/output/local variables might change their values).* |
| *(3)* | *fixed dependent parameter* | *Non-tunable dependent parameter (variable that is computed directly or indirectly from constants or parameters).* |
| *(4)* | *tunable dependent parameter* | *Tunable dependent parameter (changing an independent parameter triggers an external event (ModelExchange) or takes effect at the next Communication Point (CoSimulation), and tunable dependent parameters and tunable local variables might change their values).* |
| *(5)* | *discrete input* | *Discrete input variable from another model.* |
| *(6)* | *continuous input* | *Continuous input variable from another model.* |
| *(7)* | *constant output* | *Variable where the value never changes and that can be used in another model.* |
| *(8)* | *discrete output* | *Discrete variable that is computed in the FMU. Can be used in another model.* |
| *(9)* | *continuous output* | *Continuous variable that is computed in the FMU and can be used in another model.* |
| *(10)* | *constant local* | *Variable where the value never changes. Cannot be used in another model.* |
| *(11)* | *fixed local* | *Local variable that depends on fixed parameters only and is computed in the FMU. Cannot be used in another model. After initialization, the value of this local variable cannot change.* |
| *(12)* | *tunable local* | *Local variable that depends on tunable parameters only and is computed in the FMU. Cannot be used in another model. The value of this local variable can only change during initialization and at event instants, provided a tunable parameter was changed.* |
| *(13)* | *discrete local* | *Discrete variable that is computed in the FMU and cannot be used in another model.* |
| *(14)* | *continuous local* | *Continuous variable that is computed in the FMU and cannot be used in another model.* |
| *(15)* | *continuous independent* | *All variables are a function of the continuous-time variable marked as “independent”. Usually, this is “time”.* |

*How to treat tunable variables:*

*A parameter p is a variable that does not change its value during simulation, in other words dp/dt = 0. If the parameter "p" is changing, then Dirac impulses are introduced since dp/dt of a discontinuous constant variable "p" is a Dirac impulse. Even if this Dirac impulse would be modeled correctly by the modeling environment, it would introduce unwanted “vibrations”. Furthermore, in many cases the model equations are derived under the assumption of a constant value (like mass or capacity), and the model equations would be different if “p” would be time varying.*

*FMI for Model Exchange:*

*Therefore, “tuning a parameter” during simulation does not mean to “change the parameter online” during simulation. Instead, this is a short hand notation for:*

1. *Stop the simulation at an event instant   
   (usually, a step event, in other words after a successful integration step).*
2. *Change the values of the tunable parameters.*
3. *Compute all parameters that depend on the tunable parameters.*
4. *Newly start the simulation using as initial values the current values of all previous variables and the new values of the parameters.*

*Basically this means that a new simulation run is started from the previous FMU state with changed parameter values. With this interpretation, changing parameters online is “clean”, as long as these changes appear at an event instant.*

*FMI for Co‑Simulation:*

*Changing of tunable parameters is allowed before an fmi2DoStep call (so, whenever an input can be set with fmi2SetXXX) and before fmi2ExitInitializationMode is called (that is, before and during Initialization Mode). The FMU internally carries out event handling if necessary.*

]

Variables of the same base type (like fmi2Real) that have identical valueReference definitions are called “alias” variables. The main purpose of “alias” variables is to enhance efficiency. If two variables a and b are alias variables, then this is only allowed if the behavior of the FMU would be exactly the same if a and b were not treated as alias variables (that is, had different valueReferences). This requirement leads naturally to the following restrictions:

1. Variables a and b that can both be set with fmi2SetXXX, or variable a that can be set with fmiSetXXX and variable b that is defined with causality = ″independent″, cannot be alias variables [*since these variables are “independent” variables, and alias means that there is a constraint equation between variables (= the values are the same), these variables are no longer “independent”.  
   For example, if variables* a *and* b *have* causality = *"*parameter*", then the value references of* a *and* b *must be different. However, if variable* a *has* causality = *"*parameter*" and* b *has* causality = *"*calculatedParameter*" and* b := a*, then* a *and* b *can have the same value reference.*].
2. At most one variable of the same alias set of variables with variability ≠ "constant" can have a start attribute. [*since “*start*” variables are independent initial values.*]
3. A variable with variability = *"*constant*"* can only be aliased to another variable with variability = *"*constant*"*. It is then required that the start values of all aliased (constant) variables are identical.
4. All variables of the same alias set must all have either no <Unit> element defined, or all of them must have the same <Unit name> and the same <Unit><BaseUnit> definitions.

The aliasing of variables only means that the “value” of the variables is always identical. However, aliased variables may have different attributes, such as min/max/nominal values or description texts. [*For example, if v1, v2 are two alias variables with v1=v2 and v1.max=10 and v2.max=5, then the FMU will trigger an error if either v1 or v2 becomes larger than 5.*]

[*The dependency definition in* fmiModelDescription.ModelStructure *is completely unrelated to the alias definition. In particular, the “direct dependency” definition can be a superset of the “real” direct dependency definition, even if the “alias” information shows that this is too conservative. For example, if it is stated that the output y1 depends on input u1 and the output y2 depends on input u2, and y1 is an alias to y2, then this definition is fine, although it can be deduced that in reality neither y1 nor y2 depend on any input.*].

*[In case of different variability among the set of alias variables, and if that set of aliases does not contain an input or parameter, the variability should be the highest of the variables in the set, e.g. continuous > discrete > tunable > fixed. If the set includes a parameter or input the aliases will have the stated variability of that parameter or input.]*Type specific properties are defined in the required choice element, where exactly one of “Real”, “Integer”, “Boolean”, “String”, “Enumeration” must be present in the XML file:

 

 



The attributes are defined in section 2.2.3 (“TypeDefinitions”), except:

|  |  |
| --- | --- |
| *Attribute-Name* | *Description* |
| declaredType | If present, name of type defined with TypeDefinitions / SimpleType. The value defined in the corresponding TypeDefinition (see section 2.2.3) is used as default. [*For example, if “min” is present both in Real (of TypeDefinition) and in “Real” (of ScalarVariable), then the “min” of ScalarVariable is actually used.*] For Real, Integer, Boolean, String, this attribute is optional. For Enumeration it is required, because the Enumeration items are defined in TypeDefinitions / SimpleType. |
| start | Initial or guess value of variable. **This value is also stored in the C functions**. [*Therefore, calling* fmi2SetXXX *to set start values is only necessary, if a different value as stored in the xml file is desired.* WARNING: It is not recommended to change the start values in the *modelDescription.xml* file of an FMU, as this would break the consistency with the hard-coded start values in the C Code. This could lead to unpredictable behaviour of the FMU in different importing tools, as it is not mandatory to call *fmi2SetXXX* to set start values during initialization. Instead it is recommended to use the SSP Standard (<https://ssp-standard.org/>) to handle modified parameters of FMUs or different parameter sets.] The interpretation of start is defined by ScalarVariable / initial. A different start value can be provided with an fmi2SetXXX function before fmi2ExitInitializationMode is called (but not for variables with variability = ″constant″).  [*The standard approach is to set the start value before fmi2EnterInitializationMode. However, if the initialization shall be modified in the calling environment (for example, changing from initialization of states to steady-state initialization), it is also possible to use the start value as iteration variable of an algebraic loop: using an additional condition in the environment, such as , the actual start value is determined*.]  If initial = ″exact″ or ″approx″ or causality = ″input″, a start value must be provided.  If initial = ″calculated″ or causality = ″independent″, it is not allowed to provide a start value.  Variables with causality = "parameter" or "input", as well as variables with variability = "constant", must have a "start" value.   * If causality = "parameter", the start-value is the value of it. * If causality = "input", the start value is used by the model as value of the input, if the input is not set by the environment. * If variability = "constant", the start value is the value of the constant. * If causality = "output" or "local" then the start value is either an “initial” or a “guess” value, depending on the setting of attribute "initial". |
| derivative | If present, this variable is the derivative of variable with ScalarVariable index "derivative". [*For example, if there are 10 ScalarVariables and derivative = 3 for ScalarVariable 8, then ScalarVariable 8 is the derivative of ScalarVariable 3 with respect to the independent variable (usually time).* *This information might be especially used if an input or an output is the derivative of another input or output, or to define the states.*]  The state derivatives of an FMU are listed under element <ModelStructure><Derivatives>. All ScalarVariables listed in this element must have attribute derivative (in order that the continuous-time states are uniquely defined). |
| reinit | Only for ModelExchange (if only CoSimulation FMU, this attribute must not be present. If both ModelExchange and CoSimulation FMU, this attribute is ignored for CoSimulation): Can only be present for a continuous-time state.  If true, state can be reinitialized at an event by the FMU.  If false, state will not be reinitialized at an event by the FMU. |
| min / max | The optional attributes “min” and “max” in element “Enumeration” restrict the allowed values of the enumeration. The min/max definitions are information from the FMU to the environment defining the region in which the FMU is designed to operate, see also comment in section 2.2.3. [*If, for example, an Enumeration is defined with “name1 = -4”, “name2 = 1”, “name3 = 5”, “name4 = 11” and min=-2, max = 5, then only “name2” and “name3” are allowed*]. |

With element “Annotations” additional, tool specific data can be defined:



With Tool.name the name of the tool is defined that can interpret the “any” element. The “any” element can be an arbitrary XML data structure defined by the tool. [*Typically, additional data is defined here how to build up the menu for the variable, including the graphical layout and enabling/disabling an input field based on the values of other parameters.*]

### Definition of the Model Structure (ModelStructure)

The structure of the model is defined in element “**ModelStructure**” within “fmiModelDescription”. This structure is with respect to the underlying model equations, independently how these model equations are solved. [*For example, when exporting a model both in Model Exchange and Co-Simulation format; then the model structure is identical in both cases. The Co-Simulation FMU has either an integrator included that solves the model equations, or the discretization formula of the integrator and the model equations are solved together (“inline integration”). In both cases the model has the same continuous-time states. In the second case the internal implementation is a discrete-time system, but from the outside this is still a continuous-time model that is solved with an integration method.*]

The required part defines an ordering of the outputs and of the (exposed) derivatives, and defines the unknowns that are available during Initialization [*Therefore, when linearizing an FMU, every tool will use the same ordering for the outputs, states, and derivatives for the linearized model. The ordering of the inputs should be performed in this case according to the ordering in ModelVariables.*]A ModelExchange FMU must expose all derivatives of its continuous-time states in element <Derivatives>. A Co-Simulation FMU does not need to expose these state derivatives. [*If a Co-Simulation FMU exposes its state derivatives, they are usually not utilized for the co-simulation, but, for example, to linearize the FMU at a communication point.*]

The optional part defines in which way derivatives and outputs depend on inputs, and continuous-time states at the current super dense time instant (ModelExchange) or at the current Communication Point (CoSimulation). [*A simulation environment can utilize this information to improve the efficiency, for example, when connecting FMUs together, or when computing the partial derivative of the derivatives with respect to the states in the simulation engine.*]

ModelStructure has the following definition:



fmi2VariableDependency is defined as:



Elements of the InitialUnknowns list:





Note that attribute dependenciesKind for element InitialUnknowns has less enumeration values as dependenciesKind in the other lists.

ModelStructure consists of the following elements (see also figures above; the symbols of the mathematical equations describing the dependency are defined in section 3.1):

|  |  |
| --- | --- |
| *Element-Name* | *Description* |
| Outputs | Ordered list of all outputs, in other words a list of ScalarVariable indices where every corresponding ScalarVariable must have causality = "output" (and **every variable with causality=”output” must be listed here**). [*Note that all output variables are listed here, especially discrete and continuous outputs. The ordering of the variables in this list is defined by the exporting tool. Usually, it is best to order according to the declaration order in the source model, since then the <Outputs> list does not change if the declaration order of outputs in the source model is not changed. This is, for example, important for linearization, in order that the interpretation of the output vector does not change for a re-exported FMU.*]. Attribute dependencies defines the dependencies of the outputs from the knowns at the current super dense time instant in *Event* and in *Continuous-Time Mode* (ModelExchange) and at the current *Communication Point* (CoSimulation). The functional dependency is defined as (dependencies of variables that are fixed in *Event* and *Continuous-Time* *Mode* and at *Communication Points* are not shown): |
| Derivatives | Ordered list of all state derivatives, in other words, a list of ScalarVariable indices where every corresponding ScalarVariable must be a state derivative. *[Note that only continuous Real variables are listed here. If a state or a derivative of a state shall not be exposed from the FMU, or if states are not statically associated with a variable (due to dynamic state selection), then dummy ScalarVariables have to be introduced, for example, x[4] or xDynamicStateSet2[5]. The ordering of the variables in this list is defined by the exporting tool. Usually, it is best to order according to the declaration order of the states in the source model, since then the <Derivatives> list does not change if the declaration order of states in the source model is not changed. This is, for example, important for linearization, in order that the interpretation of the state vector does not change for a re-exported FMU.*]. The number of Unknown elements in the Derivatives element uniquely define the number of continuous time state variables, as required by the corresponding Model Exchange functions (integer argument nx of fmi2GetContinuousStates, fmi2SetcontinuousStates, fmi2GetDerivatives, fmi2GetNominalsOfContinuousStates see hereafter) that require it. The corresponding continuous-time states are defined by attribute **derivative** of the corresponding ScalarVariable state derivative element. [*Note that higher order derivatives must be mapped to first order derivatives but the mapping definition can be preserved due to attribute derivative. Example: if , then is the vector of state derivatives and attribute derivative of references , and attribute derivative of references .*]  For Co-Simulation, element “Derivatives” is ignored if capability flag providesDirectionalDerivative has a value of false, in other words, it cannot be computed. [*This is the default. If an FMU supports both ModelExchange and CoSimulation, then the “Derivatives” element might be present, since it is needed for ModelExchange. If the above flag is set to false for the CoSimulation case, then the “Derivatives” element is ignored for CoSimulation. If “inline integration” is used for a CoSimulation slave, then the model still has continuous-time states and just a special solver is used (internally the implementation results in a discrete-time system, but from the outside, it is still a continuous-time system).]*  Attribute dependencies defines the dependencies of the state derivatives from the knowns at the current super dense time instant in *Event* and in *Continuous-Time Mode* (ModelExchange) and at the current *Communication Point* (CoSimulation). The functional dependency is defined as (dependencies of variables that are fixed in *Event* and *Continuous-Time* *Mode* and at *Communication Points* are not shown): |

|  |  |
| --- | --- |
| InitialUnknowns | Ordered list of all exposed Unknowns in Initialization Mode. This list consists of all variables with   1. causality = "output" and (initial="approx" or "calculated"), and 2. causality = "calculatedParameter" and 3. all continuous-time states and all state derivatives (defined with element <Derivatives> from <ModelStructure>) with initial="approx" or "calculated" [*if a Co-Simulation FMU does not define the <Derivatives> element, (3) cannot be present.*].   The resulting list is not allowed to have duplicates (for example, if a state is also an output, it is included only once in the list). The Unknowns in this list must be ordered according to their ScalarVariable index (for example, if for two variables A and B the ScalarVariable index of A is less than the index of B, then A must appear before B in InitialUnknowns).  Attribute dependencies defines the dependencies of the Unknowns from the Knowns in *Initialization Mode* at the initial time. The functional dependency is defined as:  Since, outputs, continuous-time states and state derivatives are either present as Knowns (if initial = "exact") or as Unknowns (if initial="approx" or "calculated"), they can be inquired with fmiGetXXX in InitializationMode.  [*Example: Assume an FMU is defined in the following way:*  *Therefore, the initial state has initial = "exact" and the initial state derivative has initial="calculated". The environment can still initialize this FMU in steady-state, by using as iteration variables and adding the equations in the environment.]* |
| Unknown | An element of one of the lists above defining the unknown with a reference to the corresponding ScalarVariable element. It is assumed that at a super-dense time instant (ModelExchange) and at a Communication Point (CoSimulation) the following relationship holds:  where   * is the unknown variable defined with this element [*for example, an output or a state derivative].* * is the vector of input arguments of function *h* that changes its value in the actual Mode [*for example, continuous-time inputs in Continuous-Time Mode*]. * is the set of input arguments of function *h* that do not change their values in this Mode, but change their values in other Modes [*for example, fixed parameters in Continuous-Time Mode*].   Attribute dependencies of Unknown defines the dependency of with respect to .  [*If, for example, a continuous-time output is a function of the continuous-time inputs and , and these inputs have changed, then* fmi2SetXXX *on and must always be called before calling* fmi2GetXXX *on .*] |

Element Unknown in Outputs, Derivatives and InitialUnknowns has the following attributes:

|  |  |  |  |
| --- | --- | --- | --- |
| *Attribute-Name* | *Description* | | |
| index | The ScalarVariable index of the Unknown . [*For example, if there are 10 ScalarVariables and index = 3, then the third ScalarVariable is the unknown defined with this element.*] | | |
| dependencies | Optional attribute defining the dependencies of the unknown (directly or indirectly via auxiliary variables) with respect to . If not present, it must be assumed that the Unknown depends on all Knowns. If present as empty list, the Unknown depends on none of the Knowns. Otherwise the Unknown depends on the Knowns defined by the given ScalarVariable indices. The indices are ordered according to magnitude, starting with the smallest index.  Knowns in *Event* and *Continuous-Time Mode* (ModelExchange) and at *Communication Points* (CoSimulation) for elements Outputs, Derivatives:   * inputs (variables with causality = "input") * continuous-time states * independent variable (usually time; causality = "independent"). If an independent variable is not explicitly defined under ScalarVariables, it is assumed that the Unknown depends explicitly on the independent variable.   Knowns in *Initialization Mode* (for elements InitialUnknowns):   * inputs (variables with causality = "input") * variables with initial = "exact" [*for example, independent parameters or initial states.*] * independent variable (usually time; causality = "independent"). If an independent variable is not explicitly defined under ScalarVariables, it is assumed that the Unknown depends explicitly on the independent variable.   For Co-Simulation, “dependencies” does not list the dependency on continuous-time, if the capability flag  providesDirectionalDerivative has a value of false. In other words, the respective partial derivatives cannot be computed. | | |
| dependenciesKind | If not present, it must be assumed that the Unknown depends on the Knowns without a particular structure. Otherwise, the corresponding Known enters the equation as:  If "dependenciesKind" is present, "dependencies" must be present and must have the same number of list elements. | | |
| = dependent: | | no particular structure, ,..) |
| Only for Real unknowns : | | |
| = constant: | constant factor, where is an expression that is evaluated before fmi2EnterInitializationMode is called. | |
| Only for Real unknowns in Event and Continuous-Time Mode (ModelExchange) and at *Communication Points* (CoSimulation), and not for InitialUnknowns for Initialization Mode: | | |
| = fixed: | fixed factor, where is an expression that is evaluated before fmi2ExitInitializationMode is called. | |
| = tunable: | tunable factor, where is an expression that is evaluated before fmi2ExitInitializationMode is called and in Event Mode due to an external event (ModelExchange) or at a Communication Point (CoSimulation) | |
| = discrete: | discrete factor, where is an expression that is evaluated before fmi2ExitInitializationMode is called and in Event Mode due to an external or internal event or at a Communication Point (CoSimulation). | |
| If "dependenciesKind" is present, "dependencies" must be present and must have the same number of list elements. | | |

[*Example 1:*

*An FMU is defined by the following equations:*

*,*

*where is a continuous-time input (variability=”continuous”), is any type of input, is a Real discrete-time input (variability=”discrete”), and is a fixed parameter (variability=”fixed”). The initialization is defined by:*

*,*

*and therefore the initialization equations are:*

*This equation system can be defined as:*

<**ModelVariables**>

<**ScalarVariable** name="p" ...> … </**ScalarVariable**> <!--index="1" -->

<**ScalarVariable** name="u1" ...> … </**ScalarVariable**> <!--index="2" -->

<**ScalarVariable** name="u2" ...> … </**ScalarVariable**> <!--index="3" -->

<**ScalarVariable** name="u3" ...> … </**ScalarVariable**> <!--index="4" -->

<**ScalarVariable** name="x1" ...> … </**ScalarVariable**> <!--index="5" -->

<**ScalarVariable** name="x2" ...> … </**ScalarVariable**> <!--index="6" -->

<**ScalarVariable** name="x3" ...> … </**ScalarVariable**> <!--index="7" -->

<**ScalarVariable** name="der(x1)" ...> … </**ScalarVariable**> <!--index="8" -->

<**ScalarVariable** name="der(x2)" ...> … </**ScalarVariable**> <!--index="9" -->

<**ScalarVariable** name="der(x3)" ...> … </**ScalarVariable**> <!--index="10" -->

<**ScalarVariable** name="y" ...> … </**ScalarVariable**> <!--index="11" -->

</**ModelVariables**>

<**ModelStructure**>

<**Outputs**>

<**Unknown** index="11" dependencies="6 7" />

</**Outputs**>

<**Derivatives**>

<**Unknown** index="8" dependencies="6" />

<**Unknown** index="9" dependencies="2 4 5 6"

dependenciesKind="constant constant dependent fixed"/>

<**Unknown** index="10" dependencies="2 3 4 5 6" />

</**Derivatives**>

<**InitialUnknowns**>

<**Unknown** index="6" dependencies="2 4 5" />

<**Unknown** index="7" dependencies="2 4 5 11" />

<**Unknown** index="8" ... />

<**Unknown** index="10" ... />

</**InitialUnknowns**>

</**ModelStructure**>

*Example 2:*

*where is a continuous-time input with index=”1” and is a continuous-time output with index=”2”. The definition of the model structure is then:*

<**ModelStructure**>

<**Outputs**>

<**Unknown** index="2" dependencies="1" dependenciesKind="discrete"/>

</**Outputs**>

</**ModelStructure**>

*Note, where changes only during Event Mode ( or depending on relation that changes only at Event Mode). Therefore dependenciesKind="discrete".*

*Example 3:*

*where is a continuous-time input with index=”1” and is a continuous-time output with index=”2”. The definition of the model structure is then:*

<**ModelStructure**>

<**Outputs**>

<**Unknown** index="2" dependencies="1" dependenciesKind="dependent"/>

</**Outputs**>

</**ModelStructure**>

*Note that where changes only during Event Mode ( or depending on relation that changes only at Event Mode). Therefore dependenciesKind="dependent" because it is not a linear relationship on .*

*Example 4:*

*where* iscontinuous-time input with index="1", is a continuous-time output with index="2" and is a continuous-time derivative with index="4". The definition of the model structure is then:

<ModelVariables>  
   <ScalarVariable name="u"     , ...> … </ScalarVariable>  <!--index="1" -->  
   <ScalarVariable name="y"     , ...> … </ScalarVariable>  <!--index="2" -->  
   <ScalarVariable name="x"     , ...> … </ScalarVariable>  <!--index="3" -->  
   <ScalarVariable name="der(x)", ...> … </ScalarVariable>  <!--index="4" -->  
</ModelVariables>

<ModelStructure>  
   <Outputs>  
     <Unknown index="2" dependencies="3"  dependenciesKind="constant"/>  
   </Outputs>  
   <Derivatives>  
     <Unknown index="4"  dependencies="1"  dependenciesKind="constant"/>  
   </Derivatives>  
   <InitialUnknowns>  
     <Unknown index="2" dependencies="3" />  
     <Unknown index="4" dependencies="1" />  
   </InitialUnknowns>  
</ModelStructure>

*Defining FMU features with the* dependencies *list:*

*Note that via the dependencies list the supported features of the FMU can be defined. Examples:*

* *If a state derivative der\_x is a function of a parameter p (so of a start value of a variable with causality = "parameter" and variability = "fixed"), and the FMU does not support an iteration over p during InitializationMode (for example, to iterate over p such that the state derivative der\_x is zero), then the dependencies list of der\_x should not include p. If an FMU is imported in an environment and such an iteration is set up, then the tool can figure out that the resulting algebraic system of equations is structurally singular and therefore can reject such a definition.*
* *For standard Co-Simulation FMUs, it is common that no algebraic loops over the input/output variables nor over start-values is supported. In such a case, all dependencies lists for output variables under the InitialUnknowns element should be defined as empty lists defining that the setting of inputs and/or of start values does not influence the outputs. As a result, it is not possible to formulate algebraic loops of connected FMUs during InitializationMode.*

]

### Variable Naming Conventions (variableNamingConvention)

With attribute “variableNamingConvention” of element “fmiModelDescription”, the convention is defined how the ScalarVariable.names have been constructed. If this information is known, the environment may be able to represent the names in a better way (for example, as a tree and not as a linear list).

In the following definitions, the [EBNF](http://en.wikipedia.org/wiki/Extended_BNF) is used:

= production rule   
[ ] optional  
{ } repeat zero or more times  
| or

The names must be unique, non-empty strings.  
[*It is recommended that the names are visually clearly different from each other; but it is not required.*]

The following conventions for scalar names are defined:

**variableNamingConvention = "flat"**

name = Unicode-char { Unicode-char } // identical to xs:normalizedString

Unicode-char = any Unicode character without carriage return (#xD), line feed (#xA)  
 nor tab (#x9)

**variableNamingConvention = "structured"**

Structured names are hierarchical using “.” as a separator between hierarchies. A name consists of “\_”, letters and digits or may consist of any characters enclosed in single apostrophes. A name may identify an array element on every hierarchical level using “[...]” to identify the respective array index. A derivative of a variable is defined with “der(name)” for the first time derivative and “der(name,N)” for the N-th derivative. Examples:

vehicle.engine.speed

resistor12.u

v\_minrobot.axis.'motor #234'

der(pipe[3,4].T[14],2) // second time derivative of pipe[3,4].T[14]

The precise syntax is[[9]](#footnote-9):

name = identifier | "der(" identifier ["," unsignedInteger ] ")"

identifier = B-name [ arrayIndices ] {"." B-name [ arrayIndices ] }

B-name = nondigit { digit | nondigit } | Q-name

nondigit = "\_" | letters "a" to "z" | letters "A" to "Z"

digit = "0" | "1" | "2" | "3" | "4" | "5" | "6" | "7" | "8" | "9"

Q-name = "'" ( Q-char | escape ) { Q-char | escape } "'"

Q-char = nondigit | digit | "!" | "#" | "$" | "%" | "&" | "(" | ")" |

"\*" | "+" | "," | "-" | "." | "/" | ":" |

";" | "<" | ">" | "=" | "?" | "@" | "[" |

"]" | "^" | "{" | "}" | "|" | "~" | " "

escape = "\'" | "\"" | "\?" | "\\" | "\a" | "\b" |

"\f" | "\n" | "\r" | "\t" | "\v"

arrayIndices = "[" unsignedInteger {"," unsignedInteger} "]"

unsignedInteger = digit { digit }

~~The tree of names is mapped to an ordered list of ScalarVariable.name’s in~~ [~~depth-first~~](http://en.wikipedia.org/wiki/Depth-first_search) ~~order.~~  
*[Clarification for FMI 2.0.1: this constraint has been removed.]*

Example:

vehicle

transmission

ratio

outputSpeed

engine

inputSpeed

temperature

is mapped to the following list of ScalarVariable.name’s:

vehicle.transmission.ratio

vehicle.transmission.outputSpeed

vehicle.engine.inputSpeed

vehicle.engine.temperature

All array elements are given in a consecutive sequence of ScalarVariables. Elements of multi-dimensional arrays are ordered according to “row major” order that is elements of the last index are given in sequence.

[*For example, the vector “centerOfMass” in body “arm1” is mapped to the following ScalarVariables:*

*robot.arm1.centerOfMass[1]*

*robot.arm1.centerOfMass[2]*

*robot.arm1.centerOfMass[3]*

*For example, a controller might receive 3 rpm sensors mapped to the following variables:*

*transmission.rpms[0]  
transmission.rpms[1]  
transmission.rpms[2]*

*For example, a table T[4,3,2] (first dimension 4 entries, second dimension 3 entries, third dimension 2 entries) is mapped to the following ScalarVariables:*

*T[1,1,1]*

*T[1,1,2]*

*T[1,2,1]*

*T[1,2,2]*

*T[1,3,1]*

*T[1,3,2]*

*T[2,1,1]*

*T[2,1,2]*

*T[2,3,1]*

*…*

]

It might be that not all elements of an array are present. If they are present, they are given in consecutive order in the XML file.

*[Clarification for FMI 2.0.2: The variableNamingConvention structured does not define if array indices are 0- or 1-based.]*

## FMU Distribution

An FMU description consists of several files. An FMU implementation may be distributed in source code and/or in binary format. All relevant files are stored in a ZIP file with a pre-defined structure. The implementation must either implement all the functions of FMI for Model Exchange or all the functions of FMI for Co-Simulation or both. Specifically it is required that all functions specified for Model Exchange and/or Co-Simulation are present, even if they are only needed for capabilities that the FMU does not support. The behavior of those functions is unspecified, so while calling environments can rely on the functions being present, they cannot rely on any particular behavior for functions only needed for capabilities the FMU does not support. The extension of the ZIP file must be “**.fmu**”, for example, “HybridVehicle.fmu”. ~~The compression method used for the ZIP file must be “deflate” [~~*~~(most free tools, such as zlib, offer only the common compression method "deflate")~~*~~].~~  
Clarification in FMI 2.0.3: The compression method for all files stored in the ZIP archive must be either 8 (“deflate”), or 0 (“store”). Only files stored using compression method 8 (“deflate”) may be stored with general purpose bit 3 set. The field “version needed to extract” of the archive must not be higher than 2.0, and encryption must not be employed.   
The archive must not be a split or spanned ZIP archive. Links must not be used inside the ZIP archive. *[These restrictions ensure broad compatibility of the archive with common ZIP processing tools and libraries.]*

The ZIP format specification can be found here: https://pkware.cachefly.net/webdocs/casestudies/APPNOTE.TXT  
[*Note: especially section 4.4.17 states that backslashes "\" are forbidden as path separator, only forward slashes "/" are allowed.*]  
[*Note: non-ASCII directory names are not explicitly forbidden, but might pose a problem on different operating systems and are thus discouraged.*]

Every FMU is distributed with its own ZIP file. This ZIP file has the following structure:

// Structure of zip file of an FMU

**modelDescription.xml** // Description of FMU (required file)

**model.png** // Optional image file of FMU icon

**documentation** // Optional directory containing the FMU documentation

index**.html** // Entry point of the documentation

externalDependencies.{txt|html} // documentation of external resources required  
 // to load or simulate the FMU

<other documentation files>

licenses                    // Optional directory for licenses  
        license.{txt,html}      // Entry point for license information  
        <license files>         // For example BSD licenses

**sources** // Optional directory containing all C sources

// all needed C sources and C header files to compile and link the FMU

// with exception of: fmi2TypesPlatform.h , fmi2FunctionTypes.h and fmi2Functions.h  
 // The files to be compiled (but not the files included from these files)  
 // have to be reported in the xml-file under the structure  
 // <ModelExchange><SourceFiles> … and <CoSimulation><SourceFiles>  
 buildDescription.xml // Optional build description file

**binaries** // Optional directory containing the binaries

**win32** // Optional binaries for 32-bit Windows

<modelIdentifier>**.dll** // DLL of the FMI implementation

// (build with option "MT" to include run-time environment)

<other DLLs> // The DLL can include other DLLs

// Optional object Libraries for a particular compiler

**VisualStudio8**  // Binaries for 32-bit Windows generated with

// Microsoft Visual Studio 8 (2005)

<modelIdentifier>**.lib** // Binary libraries

**gcc3.1** // Binaries for gcc 3.1.

...

**win64** // Optional binaries for 64-bit Windows

...

**linux32** // Optional binaries for 32-bit Linux   
 <modelIdentifier>.**so** // Shared library of the FMI implementation

...

**linux64** // Optional binaries for 64-bit Linux

...

**aarch64-darwin** // Optional binaries for macOS on Apple Silicon

<modelIdentifier>.dylib

...

< If an FMU is run through one of its binaries all items in that binary folder are

recommended to be unpacked at the same location as the binary < modelIdentifier >.\*

is unpacked. If not it is likely that, if the FMU has dependencies on those items,

it will not be able to find them. >

**resources** // Optional resources needed by the FMU

< data in FMU specific files which will be read during initialization;

also more folders can be added under resources (tool/model specific).

In order for the FMU to access these resource files, the resource directory

must be available in unzipped form and the absolute path to this directory

must be reported via argument ″fmuResourceLocation″ via fmi2Instantiate. >

**extra** // Additional (meta-)data of the FMU (optional)

// additional (meta-)data that is supposed to travel with the FMU;

// see below for structure and content definition.

**terminalsAndIcons** // Optional directory containing Terminals and Icons resources

terminalsAndIcons.xml // Optional file defining the Terminals and Icons

An FMU has to implement all common functions (according to tables in sections 3.2.3 and 4.2.4). ModelExchange FMUs have to provide additionally the respective Model Exchange function, CoSimulation FMUs the Co‑Simulation functions.

The FMU must be distributed with at least one implementation, in other words either sources or one of the binaries for a particular machine. It is also possible to provide the sources and binaries for different target machines together in one zip file. The following names are standardized: for Windows: “win32”, “win64”, for Linux: “linux32”, “linux64”, for Macintosh: “darwin32”, “darwin64”, where "32" stands for "32-bit x86" and "64" for "64-bit x86" respectively. For any other platforms the "platform tuples" defined in the FMI 3.0 Specification, 2.5.1.4.1. Platform Tuple Definition, or any updated "platform tuples" published by MAP FMI on fmi-standard.org, should be used.   
Futhermore, also the names “VisualStudioX” and “gccX” are standardized and define the compiler with which the binary has been generated [*, for example VisualStudio8*]. Further names can be introduced by vendors. FMUs should contain all resources that are required to load and execute a shared library, link against a static library, or compile from source. Shared libraries should be statically linked against their dependencies [*e.g. the Visual Studio C Runtime on Windows*]. `RPATH="$ORIGIN"` should be set when building ELF binaries to allow dynamic loading of dependencies on the target machine. If the FMU depends on external resources [*e.g. shared libraries, files, or servers*] to be loaded or simulated `documentation/externalDependencies.{txt|html}` should be present to document these dependencies and how to provide them.

Typical scenarios are to provide binaries only for one machine type (for example, on the machine where the target simulator is running and for which licenses of run-time libraries are available) or to provide only sources (for example, for translation and download for a particular micro-processor). If run-time libraries cannot be shipped due to licensing, special handling is needed, for example, by providing the run-time libraries at appropriate places by the receiver.

FMI provides the means for two kinds of implementation: needsExecutionTool=true and needsExecutionTool=false. In the first case a tool specific wrapper DLL/SharedObject has to be provided as the binary, in the second a compiled or source code version of the model with its solver is stored (see section 4.3.1 for details).

In an FMU both a version for ModelExchange and for CoSimulation might be present. If in both cases the executable part is provided as DLL/SharedObject, then two different or only one library can be provided. The library names are defined in the modelIdentifier attribute of elements “fmiModelDescription.ModelExchange” and “fmiModelDescription.CoSimulation”:

[*Example for different libraries:*

binaries

win32

MyModel\_ModelExchange.dll // ModelExchange.modelIdentifier =  
 // "MyModel\_ModelExchange"

MyModel\_CoSimulation.dll // CoSimulation.modelIdentifier =  
 // "MyModel\_CoSimulation"

]

The usual distribution of an FMU will be with DLLs/SharedObjects because then further automatic processing [*(for example, importing into another tool)*] is possible.

If run-time libraries are needed by the FMU that have to be present on the target machine, then automatic processing is likely impossible. The requirements and the expected processing should be documented in the “documentation” directory in this case.

A source-based distribution might require manual interaction in order that it can be utilized. The intention is to support platforms that are not known in advance (such as HIL-platforms or micro-controllers). Typically, in such a case the complete source code in ANSI-C is provided (for example, one C source file that includes all other needed C files with the “#include” directive). All C source file names that need to be defined in a compiler directive have to be defined in the xml-file under structure <ModelExchange><SourceFiles> and <CoSimulation><SourceFiles>. These files may include other files. The #include directives with quotes ("") should be used for header-files distributed in the FMU instead of using angle brackets (<>). If default options of the compiler are sufficient, it might be then possible to automatically process such source code FMUs. An exporting tool should give documentation on how to build an executable, either via a documentation file and/or via a template makefile for a particular platform, from which a user can construct the makefile for his/her target platform. This documentation should be stored in the “documentation” directory, possibly with a link to the template makefile (stored in the “sources” directory). [*As template makefile, CMake ([www.cmake.org](http://www.cmake.org)), a cross-platform, open-source build system might be used.*]  
*[New in FMI 2.0.4:]* In addtition to the “<SourceFiles>“ element a “buildDescription.xml“ can be supplied in the sources directory (as defined in the FMI 3.0 Specification, 2.4.10. Build Configurations).  
If a “buildDescription.xml“ file is present in the “sources“ directory it should take precedence over the “<SourceFiles>“ element in the `modelDescription.xml`.

The sub-directory “licenses” can be used to bundle all license files.  
[*It is strongly recommended to include all license and copyright related information in the licenses folder of an FMU (especially but not only for contained open source software) - the license.{txt,html} file can serve  
as an entry point for describing the contained licenses. This will help the users to comply with license conditions when passing source or binary code contained in an FMU to other persons or organizations.*]

In directory “resources”, additional data can be provided in FMU specific formats, typically for tables and maps used in the FMU. This data must be read into the model at the latest during initialization (that is, before “fmi2ExitInitializationMode” is called). The actual file names in the ZIP file to access the data files can either be hard-coded in the generated FMU functions, or the file names can be provided as string parameters via the “fmi2SetString” function. [*Note that the absolute file name of the resource directory is provided by the initialization functions*]. In the case of a co-simulation implementation of needsExecutionTool=true type, the “resources” directory can contain the model file in the tool specific file format.

[*Note that the header files fmi2TypesPlatform.h and fmi2FunctionTypes.h/fmi2Functions.h are not included in the FMU due to the following reasons:*

*fmi2TypesPlatform.h makes no sense in the “****sources****” directory, because if sources are provided, then the target simulator defines this header file and not the FMU.  
This header file is not included in the “****binaries****” directory, because it is implicitly defined by the platform directory (for example, win32 for 32-bit machine or linux64 for 64-bit machine). Furthermore, the version that was used to construct the FMU can also be inquired via function fmi2GetTypesPlatform().*

*fmi2FunctionTypes.h/fmi2Functions.h are not needed in the “****sources****” directory, because they are implicitly defined by attribute fmiVersion in file* ***modelDescription.xml****. Furthermore, in order that the C-compiler can check for consistent function arguments, the header file from the target simulator should be used when compiling the C sources. It would therefore be counter-productive (unsafe) if this header file was present.   
These header files are not included in the “****binaries****” directory, since they are already utilized to build the target simulator executable.The version number of the header file used to construct the FMU can be deduced via attribute fmiVersion in file* ***modelDescription.xml*** *or via function call fmi2GetVersion().*]

*[New in FMI 2.0.2:]*

**Extra Directory:**

The ZIP archive may contain additional entries with the prefix extra/ that can be used to store additional data and meta-data. In order to avoid ambiguities and conflicts, the extra files should be provided in subdirectories using a reverse domain notation of a domain that is controlled by the entity defining the semantics and content of the additional entries *[(for example* extra/com.example/SimTool/meta.xml *or* extra/org.example.stdname/data.asd*)]*

The use of subdirectories beginning with org.modelica and org.fmi-standard is explicitly reserved for use by MAP FMI-defined layered standards, i.e. other uses must not use subdirectory names beginning with these prefixes. It is explicitly allowed for tools and users other than the original creator of an FMU to modify, add or delete entries in the extra/ directory without affecting the validity of the FMU in all other aspects.

Specifically all validation or digital signature schemes used to protect the content of the FMU should take the variability of extra file content into account *[(for example by having separate checksums or signatures for FMU core content and extra content, or not having signatures at all for extra content)].*

*[New in FMI 2.0.4:]*

**Terminals and Icons**

The optional directory `terminalsAndIcons` contains the definition of the Ports and Icons of the FMU as defined in the FMI 3.0 Specification, 2.4.9. Terminals and Icons.

# FMI for Model Exchange

This chapter contains the interface description to access the equations of a dynamic system from a C program. A schematic view of a model in “FMI for Model Exchange” format is shown in Figure 2.

Solver

**u**

**y**

Enclosing Model

**xc**

*t*

**w**

|  |  |  |
| --- | --- | --- |
| *t* | | time |
| **v**start | | variables with initial = “exact” (parameters, …) |
| **u**(t) | | inputs (continuous-time and/or discrete-time) |
| **y**(t) | | outputs (continuous-time and/or discrete-time) |
| **w**(t) | | local variables (continuous-time and/or discrete-time) |
| **z**(t) | | event indicators (continuous-time) |
| Elements of local variables **w** and/or outputs **y**: | | |
| **xc**(t) | continuous-time states (continuous between events) | |
|  |  | |

*t***0, v**start

Figure 2: Data flow between the environment and an FMU for Model Exchange:   
 Blue arrows: Information provided by the FMU.  
 Red arrows : Information provided to the FMU.  
vstart,u,y,w,xd are of type Real, Integer, Boolean, String; *t*,xc,z are of type Real.

External Model (FMU Instance)

## Mathematical Description

The goal of the Model Exchange interface is to numerically solve a system of differential, algebraic and discrete-time equations. In this version of the interface, ordinary differential equations in state-space form with events are handled (abbreviated as “hybrid ODE”). Algebraic equation systems might be contained inside the FMU. Also, the FMU might consist of discrete-time equations only, for example, describing a sampled-data controller.

The independent variable time is a tuple , where . The real part of this tuple is the independent variable of the FMU for describing the continuous-time behavior of the model between events. In this phase . The integer part of this tuple is a counter to enumerate (and therefore distinguish) the events at the same continuous-time instant . This time definition is also called “super dense time” in literature, see for instance (*Lee and Zheng 2007*). An ordering is defined on leading to the following notation[[10]](#footnote-10):

|  |  |  |
| --- | --- | --- |
| *Operation* | *Mathematical meaning* | *Description* |
| < | < < = < | is before |
| = | = = = | is identical to |
|  |  | right limit at *t.* is the largest occurring Integer index of super dense time |
|  |  | left limit at *t* |
|  |  | previous time instant (= either left limit or  previous event instant). |
|  |  | value at the right limit of *t* |
|  |  | value at the left limit of t |
|  |  | previous value (= either left limit or value from the previous event) |

[*Assume that an FMU has an event at tR=2.1 s and here a signal changes discontinuously. If no event iteration occurs, the time instant when the event occurs is defined as (2.1, 0), and the time instant when the integration is restarted is defined as (2.1, 1).*]

The hybrid ODEs supported by FMI are described as piecewise continuous-time systems. Discontinuities can occur at time instants where . These time instants are called “events”. Events can be known before hand (= time event), or are defined implicitly (= state and step events), see below. Between events, variables are either continuous or do not change their value. A variable is called discrete-time, if it changes its value only at an event instant. Otherwise the variable is called continuous-time. Only real variables can be continuous-time.

The following variable indices are used to describe the timing behavior of the corresponding variable (for example, is a discrete-time variable).

|  |  |
| --- | --- |
| *Index* | *Description* |
| *c* | A **continuous-time** variable, that is, a variable that is a continuous function of time inside each interval |
| *d* | A **discrete-time** variable, that is, a variable that changes its value only at an event instant . |
| *c+d* | A set of **continuous-time** and **discrete-time** variables |

At every event instant , variables might be discontinuous (see Figure 3).

time t

t0

t1

t2

**vc(t)**

**vd(t)**

**vd(•t1)**

**vd(t1)**

Figure 3: Piecewise-continuous variables of an FMU: continuous-time (vc) and discrete-time (vd).

An event instant *t*i is defined by one of the following conditions that give the smallest time instant:

1. The environment of the FMU triggers an event at the current time instant because at least one discrete-time input changes its value, a continuous-time input has a discontinuous change, or a tunable parameter changes its value. Such an event is called external event. [*Note that if an FMU A is connected to an FMU B, and an event is triggered for A, then potentially all outputs of A will be discontinuous at this time instant. It is therefore adviceable to trigger an external event for B at this time instant too, if an output of A is connected to B. This means to call fmi2EnterEventMode on B.*]  
   All the following events are internal events.
2. At a predefined time instant *ti* = (*Tnext*(*ti-*1), 0) that was defined at the previous event instant *ti-*1 by the FMU. Such an event is called time event.
3. At a time instant, where an event indicator *zj*(*t*) changes its domain from *zj* > 0 to *zj* ≤ 0 or from *zj* ≤ 0 to *zj* > 0 (see Figure 4 below). More precisely: An event *t* = *ti* occurs at the smallest time instant “min *t”* with *t* > *ti-1* where “(z*j*(*t*) > 0) ≠ (z*j*(*ti-1*) > 0)”. Such an event is called state event[[11]](#footnote-11). All event indicators are piecewise continuous and are collected together in one vector of real numbers **z**(*t*).

time

t0

t1

t2

**z(t)**

**z > 0**

**z ≤ 0**

Figure 4: An event occurs when the event indicator changes its domain from z > 0 to z ≤ 0 or vice versa.

1. At every completed step of an integrator, fmi2CompletedIntegratorStep must be called (provided the capability flag ModelDescription.completedIntegratorStepNotNeeded = false). An event occurs at this time instant, if indicated by the return argument enterEventMode = fmi2True. Such an event is called step event. [*Step events are, for example, used to dynamically change the (continuous) states of a model internally in the FMU, because the previous states are no longer suited numerically.*]

An FMI Model Exchange model is described by the following variables:

|  |  |
| --- | --- |
| *Variable* | *Description* |
| *t* | Independent variable time . (Variable defined with causality = "independent"). |
| **v** | A vector of all exposed variables (all variables defined in element <ModelVariables>, see section 2.2.7). A subset of the variables is selected via a subscript. Example:  **v**initial=exact are variables defined with attribute initial = "exact" (see section 2.2.7). These are independent parameters and start values of other variables, such as initial values for states, state derivatives or outputs. |
| **p** | Parameters that are constant during simulation. The symbol without a subscript references independent parameters (variables with causality = "parameter"). Dependent parameters (variables with causality = "calculatedParameter") are denoted as . |
| **u**(*t*) | Input variables. The values of these variables are defined outside of the model. Variables of this type are defined with attribute causality = "input". Whether the input is a discrete-time or continuous-time variable is defined via attribute variability = "discrete" or "continuous" (see section 2.2.7). |
| **y**(*t*) | Output variables. The values of these variables are computed in the FMU and they are designed to be used in a model connection. For instance, output variables might be used in the environment as input values to other FMUs or other submodels. Variables of this type are defined with attribute causality = "output". Whether the output is a discrete-time or continuous-time variable is defined via attribute variability = "discrete" or "continuous" (see section 2.2.7). |
| **w**(*t*) | Local variables of the FMU that cannot be used for FMU connections. Variables of this type are defined with attribute causality = "local", see section 2.2.7. |
| **z**(*t*) | A vector of real continuous-time variables utilized to define state events, see below. |
| (*t*) | A vector of real continuous-time variables representing the continuous-time states.  For notational convenience, a continuous-time state is conceptually treated as a different type of variable as an output or a local variable for the mathematical description below. In reality, a continuous-time state is however part of the outputs **y** or the local variables **w** of an FMU. |
|  | is a vector of (internal) discrete-time variables (of any type) representing the discrete states.  is the value of at the previous super dense time instant, so .  Given the previous values of the discrete-time states, , at the actual time instant *t*, all other discrete-time variables, especially the discrete states , can be computed.  Discrete states are not visible in the interface of an FMU and are only introduced here to clarify the mathematical description. Formally, a discrete state is part of the outputs **y** or the local variables **w** of an FMU. |
|  | At initialization or at an event instant, an FMU can define the next time instant , at which the next event occurs (see also the definition of events above). Note that every event removes automatically a previous definition of , and it must be explicitly defined again, if a previously defined was not triggered at the current event instant. |
|  | A vector of Boolean variables with . When entering Continuous-Time Mode all relations reported via the event indicators are fixed and during this Mode these relations are replaced by . Only during Initialization or Event Mode the domains can be changed. For notational convenience, is an abbreviation for . [*For more details, see “Remark 3” below.*] |

Computing the solution of an FMI model means to split the solution process in different phases, and in every phase different equations and solution methods are utilized. The phases can be categorized according to the following modes:

1. **Initialization Mode:**This mode is used to compute at the start time initial values for continuous-time states, , and for the previous (internal) discrete-time states, , by utilizing extra equations not present in the other modes (for example, equations to define the start value for a state or for the derivative of a state).
2. **Continuous-Time Mode:**This mode is used to compute the values of all (real) continuous-time variables between events by numerically solving ordinary differential and algebraic equations. All discrete-time variables are fixed during this phase and the corresponding discrete-time equations are not evaluated.
3. **Event Mode:**  
   This mode is used to compute new values for all continuous-time variables, as well as for all discrete-time variables that are activated at the current event instant , given the values of the variables from the previous instant. This is performed by solving algebraic equations consisting of all continuous-time and all active discrete-time equations. In FMI 2.0 there is no mechanism that the FMU can provide the information whether a discrete-time variable is active or is not active (is not computed) at an event instant. Therefore, the environment has to assume that at an event instant always all discrete-time variables are computed, although internally in the FMU only a subset might be newly computed.

When connecting FMUs together, loop structures can occur that lead to particular difficulties because linear or non-linear algebraic systems of equations in Real variables but also in Boolean or Integer variables might be present. In order to solve such systems of equations over FMUs efficiently, the dependency information is needed stating, for example, which outputs depend directly on inputs. This data is optionally provided in the XML file under element <ModelStructure>. If this data is not provided, the worst case must be assumed (for example, all output variables depend algebraically on all input variables).

[*Example:* *In* Figure 5*, two different types of connected FMUs are shown (the “dotted lines” characterize the dependency information):*

FMU1

FMU2

FMU3

FMU4

**artifical algebraic loop**

**“real” algebraic loop**

fmiSetXXX(m2,<>, …)

fmiGetXXX(m2, ...)

fmiSetXXX(m1, < >, ...)

fmiGetXXX(m1,..)

fmiSetXXX(m2, < >, ...)

fmiGetXXX(m2, ...)

*sequential calling sequence:*

*iterative calling sequence:*

In every Newton iteration evaluate:

**input**: // provided by solver

**output**: // provided to solver

fmiSetXXX(m4,<>, …)

fmiGetXXX(m4, ...)

fmiSetXXX(m3, < >, ...)

fmiGetXXX(m3,..)

Figure 5: Calling sequences for FMUs that are connected in a loop.

*In the upper diagram, FMU1 and FMU2 are connected in such a way that by an appropriate sequence of fmi2SetXXX and fmi2GetXXX calls, the FMU variables can be computed.*

*In the lower diagram, FMU3 and FMU4 are connected in such a way that a “real” algebraic loop is present. This loop might be solved iteratively with a Newton method. In every iteration the iteration variable is provided by the solver, and via the shown sequence of fmi2SetXXX and fmi2GetXXX calls, the residue is computed and is provided back to the solver. Based on the residue a new value of is provided. The iteration is terminated when the residue is close to zero.*

*These types of artifical or real algebraic loops can occur in all the different modes, such as Initialization Mode, Event Mode, and Continuous-Time Mode. Since different variables are computed in every Mode and the causality of variable computation can be different in Initialization Mode as with respect to the other two Modes, it might be necessary to solve different kinds of loops in the different Modes.*

]

In Table 1 the equations are defined that can be evaluated in the respective Mode. The following color coding is used in the table:

|  |  |
| --- | --- |
| grey | If a variable in an argument list is marked in grey, then this variable is not changing in this mode and just the last calculated value from the previous mode is internally used. For an input argument, it is not allowed to call fmi2SetXXX. For an output argument, calling fmi2GetXXX on such a variable returns always the same value in this mode. |
| green | Functions marked in green are special functions to enter or leave a mode. |
| blue | Equations and functions marked in blue define the actual computations to be performed in the respective mode. |

Function fmi2SetXXX is an abbreviation for functions fmi2SetReal, fmi2SetBoolean, fmi2SetInteger and fmi2SetString respectively. Function fmi2GetXXX is an abbreviation for functions fmi2GetReal, fmi2GetBoolean, fmi2GetInteger and fmi2GetString respectively.

[*In the following table the setting of the super dense time,), is precisely described. Tools will usually not have such a representation of time. However, super-dense time defines precisely when a new "model evaluation" starts and therefore which variable values belong to the same "model evaluation" at the same (super dense) time instant and should be stored together.*]

|  |  |
| --- | --- |
| **Equations** | **FMI functions** |
| ***Equations before Initialization Mode*** | |
| Set independent variable time and define ) | fmi2SetupExperiment |
| Set variables and that have a start value (initial = "exact" or "approx") | fmi2SetXXX |
| ***Equations during Initialization Mode*** | |
| Enter Initialization Mode at (activate initialization, discrete-time and continuous-time equations) | fmi2EnterInitializationMode |
| Set variables that have a start value with initial = "exact" (independent parameters and continuous-time states with start values  are included here) | fmi2SetXXX |
| Set continuous-time and discrete-time inputs | fmi2SetXXX |
|  | fmi2GetXXX,  fmi2GetContinuousStates, fmi2GetEventIndicators |
| Exit Initialization Mode (de-activate initialization equations) | fmi2ExitInitializationMode |
| ***Equations during Event Mode*** | |
| Enter Event Mode at with **if**  (activate discrete-time equations) | fmi2EnterEventMode (only from Continuous-Time Mode or after calling fmi2SetTime  if FMU has no continuous-time equations) |
| Set independent tunable parameters  (and do not set other parameters ) | fmi2SetXXX |
| Set continuous-time and discrete-time inputs | fmi2SetXXX |
| ~~Set continuous-time states~~ | ~~fmi2SetXXX, fmi2SetContinuousStates~~ |
| is also a function of the internal variables | fmi2GetXXX,  fmi2GetContinuousStates,  fmi2GetDerivatives  fmi2GetEventIndicators |
| Increment super dense time and define with newDiscreteStatesNeeded whether a new event iteration is required. | fmi2NewDiscreteStates |
| Set independent variable time | fmi2SetTime  (if no continuous-time equations) |
| ***Equations during Continuous-Time Mode*** | |
| Enter Continuous-Time Mode: | fmi2EnterContinuousTimeMode |
| Set independent variable time: ) | fmi2SetTime |
| Set continuous-time inputs | fmi2SetXXX |
| Set continuous-time states | fmi2SetXXX, fmi2SetContinuousStates |
| is also a function of the internal variables . | fmi2GetXXX,  fmi2GetDerivatives,  fmi2GetEventIndicators |
| Complete integrator step and return *enterEventMode* | fmi2CompletedIntegratorStep |
| ***Data types*** | |
|  | |

Table 1: Mathematical description of an FMU for Model Exchange.

[*Remark 1 – Calling Sequences:*

*In the table above, for notational convenience in every Mode one function call is defined to compute all output arguments from all inputs arguments. In reality, every scalar output argument is computed by one* fmi2GetXXX *function call. Additionally, the output argument need not be a function of all input arguments, but of only a subset from it, as defined in the xml file under* <ModelStructure>*. This is essential when FMUs are connected in a loop, as shown in* Figure 5: *For example, since depends only on , but not on , it is possible to call* fmi2SetXXX *to set , and then inquire with* fmi2GetXXX *without setting beforehand.*

*It is non-trivial to provide code for* fmi2SetXXX*,* fmi2GetXXX*, if the environment can call* fmi2SetXXX *on the inputs in quite different orders. A simple remedy is to provide the dependency information, not according to the “real” functional dependency, but according to the sorted equations in the generated code. Example:*

*Assume an FMU is described by the following equations (*u1,u2 *are inputs,* y1,y2 *are outputs,* w1,w2 *are internal variables):*

w1 = w2 + u1

w2 = u2

y1 = w1

y2 = w2

*Sorting of the equations might result in (this ordering is not unique):*

w2 := u2

y2 := w2

w1 := w2 + u1

y1 := w1

*With this ordering, the dependency should be defined as* y2 = f(u2)*,* y1 = f(u1,u2)*. When* y2 *is called first with* fmi2GetXXX*, then only* u2 *must be set first (since* y2 = f(u2)*), and the first two equations are evaluated. If later* y1 *is inquired as well, then the first two equations are not evaluated again and only the last two equations are evaluated. On the other hand, if* y1 *is inquired first, then* u1 *and* u2 *must be set first (since* y1 = f(u1,u2)*) and then all equations are computed. When* y2 *is inquired afterwards, the cached value is returned.*

*If sorting of the equations in this example would instead result in the following code:*

w2 := u2

w1 := w2 + u1

y1 := w1

y2 := w2

*then the dependency should be defined as* y2 = f(u1,u2)*,* y1 = f(u1,u2)*, because* u1 *and* u2 *must be first set, before* y2 *can be inquired with* fmi2GetXXX *when executing this code.*

*Remark 2 – Mathematical Model of Discrete-Time FMUs:*

*There are many different ways discrete-time systems are described. For FMI, the following basic mathematical model for discrete-time systems is used (other description forms must be mapped, as sketched below):*

*At an event instant, the discrete system is described by algebraic equations as function of the previous (internal) discrete-time states and the discrete-time inputs . If FMUs are connected in a loop, these algebraic equations are called iteratively, until the solution is found. If the actual discrete-time states and the previous discrete-time states are not identical, the discrete-time states are updated, the Integer part of the time is incremented and a new event iteration is performed. Other discrete-time models must be mapped to this description form. Examples:*

* *Synchronous systems:  
  A synchronous system, such as Lucid Synchrone (Pouzet 2006) or Modelica 3.3 (Modelica 2012), is called periodically, and at every sample instant the discrete-time equations are evaluated exactly once. An FMU of this type can be implemented by activating the model equations only at the first event iteration and returning always from fmi2NewDiscreteStates. Furthermore, the discrete-time states are not updated by fmi2NewDiscreteStates, but as first action before the discrete-time equations are evaluated, in order that (= value at the previous clock tick) and (value at the latest clock tick) have reasonable values between clock ticks.*
* *State machines with one memory location for a state:  
  In such a system there is only one memory location for a discrete-time state and not two, and therefore a discrete-time state is updated in the statement where it is assigned (and not in fmi2NewDiscreteStates). As a result, fmi2NewDiscreteStates is basically just used to start a new (super dense) time instant. This is unproblematic, as long as no algebraic loops occur. FMUs of this type can therefore not be used in “real” algebraic loops if the involved variables depend on a discrete-time state. This restriction is communicated to the environment of the FMU by the ScalarVariable definition of the corresponding input with flag canHandleMultipleSetPerTimeInstant=false (so an input with this flag is not allowed to be called in an algebraic loop).*

*Remark 3 – Event Indicators / Freezing Relations:*

*In the above table, vector* **r** *is used to collect all relations together that are utilized in the event indicators* **z***. In Continuous-Time Mode all these relations are “frozen” and do not change during the evaluations in the respective Mode. This is indicated in the table above by computing* **r** *when entering the Continuous-Time Mode and providing* **r** *as (internal) input argument to the evaluation functions. Example:*

*An equation of the form*

*y* = **if** *x1* > x2 **or** x1 < x3 **then** +1 **else** -1;

*can be implemented in the FMU as:*

z1 := x1 – x2;  
z2 := x3 – x1;  
**if** InitializationMode **or** EventMode **then** r1 := z1 > 0;  
 r2 := z2 > 0;  
**end if;**  
y = **if** r1 **or** r2 **then** +1 **else** -1

*Therefore, the original if-clause is evaluated in this form only during Initialization and Event Mode. In Continuous-Time Mode this equation is evaluated as:*

*z1 = x1 – x2;  
z2 = x3 – x1  
y* = **if** *r1* **or** *r2* **then** +1 **else** -1;

*and when entering Continuous-Time Mode r1 and r2 are computed as*

*r1* = *z1 > 0  
r2 = z2 > 0*

*When z1 changes from z1 > 0 to z1 <= 0 or vice versa, or z2 correspondingly, the integration is halted, and the environment must call fmi2EnterEventMode.*

*An actual implementation will pack the code in an impure function, say Greater(..), resulting in:*

*y* = **if** Greater(*x1-x2,..)* **or** Greater(x3-x1,..) **then** +1 **else** -1;

*Furthermore, a hysteresis should be added for the event indicators.*

*Remark 4 – Pure Discrete-Time FMUs:*

*If an FMU has only discrete-time equations (and no variables with variability = “continuous”), then the environment need not call* fmi2EnterContinuousTimeMode *but can directly call* fmi2SetTime *to set the value of the next event instant, before* fmi2EnterEventMode *is called.*

*This is an optional optimization for the master, the FMU must support all functions that are required for a continuous time FMU and should run in a master that treats it as such.  
If a pure discrete time FMU has state events and uses event indicators, it has to enter continuousTimeMode to evaluate these. In fact, it is no longer a Pure Discrete time FMU but this was not clearly defined in 2.0 so this clarification is needed for 2.0.1*]

An FMU is initialized in Initialization Mode with . The input arguments to this function consist of the input variables (= variables with causality = ″input″), of the independent variable (= variable with causality = ″independent″; usually the default value ″time″), and of all variables that have a start value with (explicitly or implicitly) initial = ″exact″ in order to compute the continuous-time states and the output variables at the initial time *t*0. In the above table, the variables with initial = exact are collected together in variable . For example, initialization might be defined by providing initial start values for the states, , or by stating that the state derivatives are zero (). Initialization is a difficult topic by itself, and it is required that an FMU solves a well-defined initialization problem inside the FMU in Initialization Mode.

After calling fmi2ExitInitializationMode, the FMU is implicitly in Event Mode, and all discrete-time and continuous-time variables at the initial time instant can be calculated. If these variables are present in an algebraic loop, iteration can be used to compute them. Once finalized, fmi2NewDiscreteStates must be called, and depending on the value of the return argument, the FMU either continues the event iteration at the initial time instant or switches to Continuous-Time Mode.

After switching to Continuous-Time Mode, the integration is started. Basically, in this phase the derivatives of the continuous states are computed. If FMUs and/or submodels are connected together, then the inputs of these models are the outputs of other models, and therefore, the corresponding FMU outputs must be computed. Whenever result values shall be stored, usually at output points defined before the start of the simulation, the fmi2GetXXX function with respect to the desired variables must be called.

Continuous integration is stopped at an event instant. An event instant is determined by a time, state or step event, or by an external event triggered by the environment. In order to determine a state event, the event indicators **z** have to be inquired at every completed integrator step. Once the event indicators signal a change of their domain, an iteration over time is performed between the previous and the actual completed integrator step, in order to determine the time instant of the domain change up to a certain precision.

After an event is triggered, the FMU needs to be switched to Event Mode. In this mode, systems of equations over connected FMUs might be solved (similarily as in Continuous-Time Mode). Once convergence is reached, fmi2NewDiscreteStates(..) must be called to increment super dense time (and conceptually update the discrete-time states defined internally in the FMU by ). Depending on the discrete-time model, a new event iteration might be needed (for example, because the FMU describes internally a state machine and transitions are still able to fire, but new inputs shall be taken into account).

The function calls in the table above describe precisely which input arguments are needed to compute the desired output argument(s). There is no 1:1 mapping of these mathematical functions to C functions. Instead, all input arguments are set with fmi2SetXXX(..) C-function calls, and then the result argument(s) can be determined with the C functions defined in the right column of the above table. This technique is discussed in detail in section 3.2.1. [*In short: For efficiency reasons, all equations from the table above will usually be available in one (internal) C-function. With the C functions described in the next sections, input arguments are copied into the internal model data structure only when their value has changed in the environment. With the C functions in the right column of the table above, the internal function is called in such a way that only the minimum needed equations are evaluated. Hereby, variable values calculated from previous calls can be reused. This technique is called “caching” and can significantly enhance the simulation efficiency of real-world models.*]

## FMI Application Programming Interface

This section contains the interface description to evaluate different model parts from a C program.

### Providing Independent Variables and Re-initialization of Caching

Depending on the situation, different variables need to be computed. In order to be efficient, it is important that the interface requires only the computation of variables that are needed in the present context. For example, during the iteration of an integrator step, only the state derivatives need to be computed provided the output of a model is not connected; it might be that at the same time instant other variables are needed. For example, if an integrator step is completed, the event indicator functions need to be computed as well. If the state derivatives have already been computed at the present time instant, then it is important for efficiency that they are not newly computed in the call to compute the event indicator functions. This means, the state derivatives shall be reused from the previous call. This feature is called “caching of variables” in the sequel.

Caching requires that the model evaluation can detect when the input arguments, like time or states, have changed. This is achieved by setting them explicitly with a function call, since every such function call signals precisely a change of the corresponding variables. For this reason, this section contains functions to set the input arguments of the equation evaluation functions. This is unproblematic for time and states, but is more involved for parameters and inputs, since the latter may have different data types.

|  |  |
| --- | --- |
| fmi2Status fmi2SetTime(fmi2Component c, fmi2Real time); | |
|  | Set a new time instant and re-initialize caching of variables that depend on time, provided the newly provided time value is different to the previously set time value (variables that depend solely on constants or parameters need not to be newly computed in the sequel, but the previously computed values can be reused). |
| fmi2Status fmi2SetContinuousStates(fmi2Component c, **const** fmi2Real x[],   **sizet** nx); | |
|  | Set a new (continuous) state vector and re-initialize caching of variables that depend on the states. Argument nx is the length of vector x and is provided for checking purposes (variables that depend solely on constants, parameters, time, and inputs do not need to be newly computed in the sequel, but the previously computed values can be reused). Note that the continuous states might also be changed in Event Mode. Note: fmi2Status = fmi2Discard is possible. |
| fmi2Status fmi2SetXXX(..); | |
|  | Set new values for (independent) parameters, start values and inputs and re-initialize caching of variables that depend on these variables. The details of these functions are defined in section 2.1.7. |

[*The functions above have the slight drawback that values must always be copied. For example, a call to “fmi2SetContinuousStates” will provide the actual states in a vector, and this function has to copy the values in to the internal model data structure “c” so that subsequent evaluation calls can utilize these values. If this turns out to be an efficiency issue, a future release of FMI might provide additional functions to provide the address of a memory area where the variable values are present.*]

### Evaluation of Model Equations

This section contains the core functions to evaluate the model equations. Before one of these functions can be called, the appropriate functions from the previous section have to be used, to set the input arguments to the current model evaluation.

|  |  |
| --- | --- |
| fmi2Status fmi2EnterEventMode(fmi2Component c); | |
|  | The model enters Event Mode from the Continuous-Time Mode and discrete-time equations may become active (and relations are not “frozen”). |
| fmi2Status fmi2NewDiscreteStates(fmi2Component c,   fmi2EventInfo\* fmi2eventInfo);  **typedef struct**{  fmi2Boolean newDiscreteStatesNeeded;  fmi2Boolean terminateSimulation;  fmi2Boolean nominalsOfContinuousStatesChanged;  fmi2Boolean valuesOfContinuousStatesChanged;  fmi2Boolean nextEventTimeDefined;  fmi2Real nextEventTime; // next event if nextEventTimeDefined=fmi2True  } fmi2EventInfo; | |
|  | The FMU is in Event Mode and the super dense time is incremented by this call.  If the super dense time before a call to fmi2NewDiscreteStates was , then the time instant after the call is .  If return argument fmi2eventInfo->newDiscreteStatesNeeded = fmi2True, the FMU should stay in Event Mode, and the FMU requires to set new inputs to the FMU (fmi2SetXXX on inputs) to compute and get the outputs (fmi2GetXXX on outputs) and to call fmi2NewDiscreteStates again. Depending on the connection with other FMUs, the environment shall   * call fmi2Terminate, if terminateSimulation = fmi2True is returned by at least one FMU. * call fmi2EnterContinuousTimeMode if all FMUs return newDiscreteStatesNeeded = fmi2False. * stay in Event Mode otherwise.   When the FMU is terminated, it is assumed that an appropriate message is printed by the logger function (see section 2.1.5) to explain the reason for the termination.  If nominalsOfContinuousStatesChanged = fmi2True, then the nominal values of the states have changed due to the function call and can be inquired with fmi2GetNominalsOfContinuousStates.  If valuesOfContinuousStatesChanged = fmi2True. then at least one element of the continuous state vector has changed its value due to the function call. The new values of the states can be retrieved with fmi2GetContinuousStates or individually for each state for which reinit = "true" by calling getReal. If no element of the continuous state vector has changed its value, valuesOfContinuousStatesChanged must return fmi2False. [*If* fmi2True *would be returned in this case, an infinite event loop may occur.*]  If nextEventTimeDefined = fmi2True, then the simulation shall integrate at most until time = nextEventTime, and shall call fmi2EnterEventMode at this time instant. If integration is stopped before nextEventTime, for example, due to a state event, the definition of nextEventTime becomes obsolete. |
| fmi2Status fmi2EnterContinuousTimeMode(fmi2Component c); | |
|  | The model enters Continuous-Time Mode and all discrete-time equations become inactive and all relations are “frozen”.  This function has to be called when changing from Event Mode (after the global event iteration in Event Mode over all involved FMUs and other models has converged) into Continuous-Time Mode.  [*This function might be used for the following purposes:*   * *If the FMU stores results internally on file, then the results after the initialization and/or the event has been processed can be stored.* * *If the FMU contains dynamically changing states, then a new state selection might be performed with this function.*] |
| fmi2Status fmi2CompletedIntegratorStep(fmi2Component c,  fmi2Boolean noSetFMUStatePriorToCurrentPoint,  fmi2Boolean\* enterEventMode,  fmi2Boolean\* terminateSimulation); | |
|  | This function must be called by the environment after every completed step of the integrator provided the capability flag completedIntegratorStepNotNeeded = false.  Argument noSetFMUStatePriorToCurrentPoint is fmi2True if fmi2SetFMUState will no longer be called for time instants prior to current time in this simulation run [*the FMU can use this flag to flush a result buffer*].  The function returns enterEventMode to signal to the environment if the FMU shall call fmi2EnterEventMode, and it returns terminateSimulation to signal if the simulation shall be terminated. If enterEventMode = fmi2False and terminateSimulation = fmi2False the FMU stays in Continuous-Time Mode without calling fmi2EnterContinuousTimeMode again.  When the integrator step is completed and the states are modified by the integrator afterwards (for example, correction by a BDF method), then fmi2SetContinuousStates(..) has to be called with the updated states before fmi2CompletedIntegratorStep(..) is called.  When the integrator step is completed and one or more event indicators change sign (with respect to the previously completed integrator step), then the integrator or the environment has to determine the time instant of the sign change that is closest to the previous completed step up to a certain precision (usually a small multiple of the machine epsilon). This is usually performed by an iteration where time is varied and state variables needed during the iteration are determined by interpolation. Function fmi2CompletedIntegratorStep must be called *after* this state event location procedure and *not* after the successful computation of the time step by the integration algorithm. The intended purpose of the function call is to indicate to the FMU that at this stage all inputs and state variables have valid (accepted) values.  After fmi2CompletedIntegratorStep is called, it is still allowed to go back in time (calling fmi2SetTime) and inquire values of variables at previous time instants with fmi2GetXXX [*for example, to determine values of non-state variables at output points*]. However, it is not allowed to go back in time over the previous completedIntegratorStep or the previous fmi2EnterEventMode call.  [*This function might be used, for example, for the following purposes:*   1. *Delays: All variables that are used in a “delay(..)” operator are stored in an appropriate buffer and the function returns with* enterEventMode = fmi2False and terminateSimulation = fmi2False 2. *Dynamic state selection: It is checked whether the dynamically selected states are still numerically appropriate. If yes, the function returns with enterEventMode = fmi2False otherwise with enterEventMode = fmi2True. In the latter case, fmi2EnterEventMode(..) has to be called and the states are dynamically changed by a subsequent* fmi2NewDiscreteStates(..)*.*   *Note that this function is not used to detect time or state events, for example, by comparing event indicators of the previous with the current call of fmi2CompletedIntegratorStep(..). These types of events are detected in the environment, and the environment has to call fmi2EnterEventMode(..) independently in these cases, whether the return argument enterEventMode of fmi2CompletedIntegratorStep(..) is fmi2True or fmi2False.*  ] |
| fmi2Status fmi2GetDerivatives (fmi2Component c, fmi2Real derivatives[],  **sizet** nx);  fmi2Status fmi2GetEventIndicators(fmi2Component c, fmi2Real eventIndicators[],  **sizet** ni); | |
|  | Compute state derivatives and event indicators at the current time instant and for the current states. The derivatives are returned as a vector with “nx” elements. A state event is triggered when the domain of an event indicator changes from *zj* > 0 to *zj* ≤ 0 or vice versa. The FMU must guarantee that at an event restart *zj* ≠ 0, for example, by shifting *zj* with a small value. Furthermore, *zj* should be scaled in the FMU with its nominal value (so all elements of the returned vector “eventIndicators” should be in the order of “one”). The event indicators are returned as a vector with “ni” elements.  The ordering of the elements of the derivatives vector is identical to the ordering of the state vector (for example, derivatives[2] is the derivative of x[2]). Event indicators are not necessarily related to variables on the Model Description File.  Note: fmi2Status = fmi2Discard is possible for both functions. |
| fmi2Status fmi2GetContinuousStates(fmi2Component c, fmi2Real x[], **sizet** nx); | |
|  | Return the new (continuous) state vector x. |
| fmi2Status fmi2GetNominalsOfContinuousStates(fmi2Component c,   fmi2Real x\_nominal[], **sizet** nx); | |
|  | Return the nominal values of the continuous states. This function should always be called after calling function fmi2NewDiscreteStates if it returns with eventInfo-> nominalsOfContinuousStatesChanged = fmi2True, since then the nominal values of the continuous states have changed [*for example, because the association of the continuous states to variables has changed due to internal dynamic state selection*]. If the FMU does not have information about the nominal value of a continuous state i, a nominal value x\_nominal[i] = 1.0 should be returned. Note that it is required that x\_nominal[i] > 0.0 [*Typically, the nominal values of the continuous states are used to compute the absolute tolerance required by the integrator. Example:*  absoluteTolerance[i] = 0.01\*tolerance\*x\_nominal[i];] |

### State Machine of Calling Sequence

Every implementation of the FMI must support calling sequences of the functions according to the following state chart:



Figure 6: Calling sequence of Model Exchange C functions in form of an UML 2.0 state machine.

The objective of the start chart is to define the allowed calling sequences for functions of the FMI: Calling sequences not accepted by the state chart are not supported by the FMI. The behavior of an FMU is undefined for such a calling sequence. For example, the state chart indicates that when an FMU for Model Exchange is in state “Continuous-Time Mode”, a call to fmi2SetReal for a discrete input is not supported. The state chart is given here as UML 2.0 state machine. If a transition is labelled with one or more function names (for example, fmi2GetReal, fmi2GetInteger), this means that the transition is taken if any of these functions is successfully called. Note the FMU can always determine in which state it is since every state is entered by a particular function call (such as fmi2EnterEventMode), or a particular return value (such as fmi2Fatal).  
[*Bugfixes in FMI 2.0.1: Note that there was an inconsistency in FMI 2.0 in the state graph and the table regarding if fmi2GetEventIndicators is allowed to be called in initializationMode. The table (see further down) is correct and fmi2GetEventIndicators can be called in initializationMode.  
Additionally the function fmi2GetDerivatives may by called in initializationMode.*]

The transition conditions "external event", "time event", and "state event" are defined in section 3.1. Each state of the state machine corresponds to a certain phase of a simulation as follows:

**Instantiated**:  
In this state, start and guess values (= variables that have initial = ″exact″ or ″approx″) and variability ≠ "constant" can be set, this does not include inputs as they do not have an *initial* attribute.

**Initialization Mode:**In this state, equations are active to determine all continuous-time states, as well as all outputs (and optionally other variables exposed by the exporting tool). The variables that can be retrieved by fmi2GetXXX calls are (1) defined in the xml file under <ModelStructure><InitialUnknowns> and (2) variables with causality = "output". Variables with initial = ″exact″ and variability ≠ "constant", as well as variables with causality = "input" can be set.

**Continuous-Time Mode**:  
In this state, the continuous-time model equations are active and integrator steps are performed. The event time of a state event may be determined if a domain change of at least one event indicator is detected at the end of a completed integrator step.

**Event Mode**:  
If an event is triggered in Continuous-Time Mode, Event Mode is entered by calling fmi2EnterEventMode. In this mode all continuous-time and discrete-time equations are active and the unknowns at an event can be computed and retrieved. After an event is completely processed, fmi2NewDiscreteStates must be called and depending on the return argument, newDiscreteStatesNeeded, the state chart stays in Event Mode or switches to Continuous-Time Mode. When the Initialization Mode is terminated with fmi2ExitInitializationMode, then Event Mode is directly entered, and the continuous-time and discrete-time variables at the initial time are computed based on the initial continuous-time states determined in the Initialization Mode.

**terminated**:  
In this state, the solution at the final time of a simulation can be retrieved.

Note that simulation backward in time is only allowed over continuous time intervals. As soon as an event occurs (fmi2EnterEventMode was called), going back in time is forbidden, because fmi2EnterEventMode/fmi2NewDiscreteStates can only compute the next discrete state, not the previous one.

Note that during Initialization, Event, and Continuous-Time Mode, input variables can be set with fmi2SetXXX and output variables can be retrieved with fmi2GetXXX interchangeably according to the model structure defined under element <ModelStructure> in the xml-file. [*For example, if one output* y1 *depends on two inputs* u1*,* u2*, then these two inputs must be set, before* y1 *can be retrieved. If additionally an output* y2 *depends on an input* u3*, then* u3 *can be set and* y2 *can be retrieved afterwards. As a result, artificial or “real” algebraic loops over connected FMUs in any of these three modes can be handled by using appropriate numerical algorithms.*]

The allowed function calls in the respective states are summarized in the following table (functions marked in “yellow” are only available for “Model Exchange”, the other functions are available both for “Model Exchange” and “Co-Simulation”):

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **FMI 2.0 for Model Exchange** | | | | | | | |  |
| **Function** | start, end | instantiated | Initialization Mode | Event Mode | Continuous-Time Mode | terminated | error | fatal |  |
| fmi2GetTypesPlatform | x | x | x | x | x | x | x |  |  |
| fmi2GetVersion | x | x | x | x | x | x | x |  |  |
| fmi2SetDebugLogging |  | x | x | x | x | x | x |  |  |
| fmi2Instantiate | x |  |  |  |  |  |  |  |  |
| fmi2FreeInstance |  | x | x | x | x | x | x |  |  |
| fmi2SetupExperiment |  | x |  |  |  |  |  |  |  |
| fmi2EnterInitializationMode |  | x |  |  |  |  |  |  |  |
| fmi2ExitInitializationMode |  |  | x |  |  |  |  |  |  |
| fmi2Terminate |  |  |  | x | x |  |  |  |  |
| fmi2Reset |  | x | x | x | x | x | x |  |  |
| fmi2GetReal |  |  | 2 | x | x | x | 7 |  |  |
| fmi2GetInteger |  |  | 2 | x | x | x | 7 |  |  |
| fmi2GetBoolean |  |  | 2 | x | x | x | 7 |  |  |
| fmi2GetString |  |  | 2 | x | x | x | 7 |  |  |
| fmi2SetReal |  | 1 | 3 | 4 | 5 |  |  |  |  |
| fmi2SetInteger |  | 1 | 3 | 4 |  |  |  |  |  |
| fmi2SetBoolean |  | 1 | 3 | 4 |  |  |  |  |  |
| fmi2SetString |  | 1 | 3 | 4 |  |  |  |  |  |
| fmi2GetFMUstate |  | x | x | x | x | x | 7 |  |  |
| fmi2SetFMUstate |  | x | x | x | x | x | x |  |  |
| fmi2FreeFMUstate |  | x | x | x | x | x | x |  |  |
| fmi2SerializedFMUstateSize |  | x | x | x | x | x | x |  |  |
| fmi2SerializeFMUstate |  | x | x | x | x | x | x |  |  |
| fmi2DeSerializeFMUstate |  | x | x | x | x | x | x |  |  |
| fmi2GetDirectionalDerivative |  |  | x | x | x | x | 7 |  |  |
| fmi2EnterEventMode |  |  |  | x | x |  |  |  |  |
| fmi2NewDiscreteStates |  |  |  | x |  |  |  |  |  |
| fmi2EnterContinuousTimeMode |  |  |  | x |  |  |  |  |  |
| fmi2CompletedIntegratorStep |  |  |  |  | x |  |  |  |  |
| fmi2SetTime |  |  |  | 8 | x |  |  |  |  |
| fmi2SetContinuousStates |  |  |  |  | x |  |  |  |  |
| fmi2GetEventIndicators |  |  | x | x | x | x | 7 |  |  |
| fmi2GetContinuousStates |  |  | x | x | x | x | 7 |  |  |
| fmi2GetDerivatives |  |  | x | x | x | x | 7 |  |  |
| fmi2GetNominalsOfContinuousStates |  | x | x | x | x | x | 7 |  |  |
|  |  |  |  |  |  |  |  |  |  |

**x** means: call is allowed in the corresponding state

**number** means: call is allowed if the indicated condition holds:

**1** for a variable with variability ≠ "constant" that has initial = "exact" or "approx"

**2** for a variable with causality = "output" or variables listed under <ModelStructure><InitalUnkowns>

**3** for a variable with variability≠"constant" that has initial = "exact", or causality = "input"

**4** for a variable with causality = "input", or   
 (causality = "parameter" and variability = "tunable")

**5** for a variable with causality = "input" and variability = "continuous"

[Clarification in FMI 2.0.1: This rule regarding a continuous-time state variable is not shown in the state machine diagram above but shall be applied.]

**7** always, but retrieved values are usable for debugging only

**8** only for a pure discrete-time FMU. This exits the current event mode and sets the time for the next event instant. fmi2NewDiscreteStates must have been called with newDiscreteStatesNeeded = fmi2False at least once before this can be done.

### Pseudocode Example

In the following example, the usage of the fmi2XXX functions is sketched in order to clarify the typical calling sequence of the functions in a simulation environment. The example is given in a mix of pseudocode and C, in order to keep it small and understandable. Furthermore, it is assumed that one FMU is directly integrated in a simulation environment. If the FMU would be used inside another model, additional code is needed, especially initialization and event iteration has to be adapted.

|  |
| --- |
| *m = M\_fmi2Instantiate("m", ...) // "m" is the instance name*  *// "M\_" is the MODEL\_IDENTIFIER*  *nx = ... // number of states, from XML file*  *nz = ... // number of event indicators, from XML file*  *Tstart = 0 // could also be retrieved from XML file*  *Tend = 10 // could also be retrieved from XML file*  *dt = 0.01 // fixed step size of 10 milli-seconds*  *// set the start time*  *time = Tstart*  *// set variable start values (of "ScalarVariable / <type> / start")*  *M\_fmi2SetReal/Integer/Boolean/String(m, ...)*  *// initialize*  *// determine continuous and discrete states*  *M\_fmi2SetupExperiment(m,fmi2False,0.0, Tstart, fmi2True,Tend)*  *M\_fmi2EnterInitializationMode(m)*  *// set the input start values at time = Tstart*  *M\_fmi2SetReal/Integer/Boolean/String(m, ...)*  *M\_fmi2ExitInitializationMode(m)*  *initialEventMode = fmi2True*  *enterEventMode = fmi2False*  *timeEvent = fmi2False*  *stateEvent = fmi2False*  *previous\_z = zeros(nz)*  *// retrieve initial state x and*  *// nominal values of x (if absolute tolerance is needed)*  *M\_fmi2GetContinuousStates(m, x, nx)*  *M\_fmi2GetNominalsOfContinuousStates(m, x\_nominal, nx)*  *// retrieve solution at t=Tstart, for example, for outputs*  *M\_fmi2GetReal/Integer/Boolean/String(m, ...)*  *do*  *// handle events*  *if initialEventMode or enterEventMode or timeEvent or stateEvent then*  *if not initialEventMode then*  *M\_fmi2EnterEventMode(m)*  *end if*  *// event iteration*  *eventInfo.newDiscreteStatesNeeded = fmi2True;*  *valuesOfContinuousStatesChanged = fmi2False;*  *nominalsOfContinuousStatesChanged = fmi2False*  *while eventInfo.newDiscreteStatesNeeded loop*  *// set inputs at super dense time point*  *M\_fmi2SetReal/Integer/Boolean/String(m, ...)*  *// update discrete states*  *M\_fmi2NewDiscreteStates(m, &eventInfo)*  *// getOutput at super dense time point*  *M\_fmi2GetReal/Integer/Boolean/String(m, ...)*  *valuesOfContinuousStatesChanged =*  *valuesOfContinuousStatesChanged or eventInfo.valuesOfContinuousStatesChanged;*  *nominalsOfContinuousStatesChanged =*  *nominalsOfContinuousStatesChanged or eventInfo.nominalsOfContinuousStatesChanged;*  *if eventInfo.terminateSimulation then goto TERMINATE\_MODEL*  *end while*  *// enter Continuous-Time Mode*  *M\_fmi2EnterContinuousTimeMode(m)*  *// retrieve solution at simulation (re)start*  *M\_fmi2GetReal/Integer/Boolean/String(m, ...)*  *if initialEventMode or valuesOfContinuousStatesChanged then*  *// the model signals a value change of states, retrieve them*  *M\_fmi2GetContinuousStates(m, x, nx)*  *end if*  *if initialEventMode or nominalsOfContinuousStatesChanged then*  *// the meaning of states has changed; retrieve new nominal values*  *M\_fmi2GetNominalsOfContinuousStates(m, x\_nominal, nx)*  *end if*  *if eventInfo.nextEventTimeDefined then*  *tNext = min(eventInfo.nextEventTime, Tend)*  *else*  *tNext = Tend*  *end if*  *initialEventMode = fmi2False*  *end if*  *if time >= Tend then*  *goto TERMINATE\_MODEL*  *end if*  *// compute derivatives*  *M\_fmi2GetDerivatives(m, der\_x, nx)*  *// advance time*  *h = min(dt, tNext-time)*  *time = time + h*  *M\_fmi2SetTime(m, time)*  *// set continuous inputs at t = time*  *M\_fmi2SetReal(m, ...)*  *// set states at t = time and perform one step*  *x = x + h \* der\_x // forward Euler method*  *M\_fmi2SetContinuousStates(m, x, nx)*  *// get event indicators at t = time*  *M\_fmi2GetEventIndicators(m, z, nz)*  *// detect events, if any*  *timeEvent = time >= tNext*  *stateEvent = sign(z) <> sign(previous\_z) or previous\_z != 0 && z == 0*  *previous\_z = z*  *// inform the model about an accepted step*  *M\_fmi2CompletedIntegratorStep(m, fmi2True, &enterEventMode, &terminateSimulation)*  *// get continuous output*  *M\_fmi2GetReal(m, ...)*  *until terminateSimulation*  *// terminate simulation and retrieve final values*  *TERMINATE\_MODEL:*  *M\_fmi2Terminate(m)*  *M\_fmi2GetReal/Integer/Boolean/String(m, ...)*  *// cleanup*  *M\_fmi2FreeInstance(m)* |

In the code above, errors are not handled. Typically, fmi2XXX function calls are performed in the following way:

status = M\_fmi2GetDerivatives(m, der\_x, nx);

switch ( status ) { case fmi2Discard: ....; break; // reduce step size and try again

case fmi2Error : ....; break; // cleanup and stop simulation

case fmi2Fatal : ....; } // stop using the model

The switch statement could also be stored in a macro to simplify the code.

## FMI Description Schema

This is defined in 2.2. Additionally, the Model Exchange-specific element “ModelExchange” is defined in the next section.

### Model Exchange FMU (ModelExchange)

If the XML file defines an FMU for Model Exchange, element “ModelExchange” must be present. It is defined as:





The following attributes are defined (all of them are optional, with exception of “modelIdentifier”):

|  |  |
| --- | --- |
| *Attribute Name* | *Description* |
| modelIdentifier | Short class name according to C syntax, for example "A\_B\_C". Used as prefix for FMI functions if the functions are provided in C source code or in static libraries, but not if the functions are provided by a DLL/SharedObject. modelIdentifier is also used as name of the static library or DLL/SharedObject. See also section 2.1.1. |
| needsExecutionTool | If true, a tool is needed to execute the model and the FMU just contains the communication to this tool. [*Typically, this information is only utilized for information purposes. For example, when loading an FMU with* needsExecutionTool = true*, the environment can inform the user that a tool has to be available on the computer where the model is instantiated. The name of the tool can be taken from attribute* generationTool *of* fmiModelDescription.] |
| completedIntegratorStepNotNeeded | If true, function fmi2CompletedIntegratorStep need not be called (this gives a slightly more efficient integration). If it is called, it has no effect. If false (the default), the function must be called after every completed integrator step, see section 3.2.2. |
| canBeInstantiatedOnlyOncePerProcess | This flag indicates cases (especially for embedded code), where only one instance per FMU is possible  (multiple instantiation is default = false; if multiple instances are needed and this flag = true, the FMUs must be instantiated in different processes). |
| canNotUseMemoryManagementFunctions | If true, the FMU uses its own functions for memory allocation and freeing only. The callback functions allocateMemory and freeMemory given in fmi2Instantiate are ignored. |
| canGetAndSetFMUstate | If true, the environment can inquire the internal FMU state and can restore it. That is, functions fmi2GetFMUstate, fmi2SetFMUstate, and fmi2FreeFMUstate are supported by the FMU. |
| canSerializeFMUstate | If true, the environment can serialize the internal FMU state, in other words, functions fmi2SerializedFMUstateSize, fmi2SerializeFMUstate, fmi2DeSerializeFMUstate are supported by the FMU. If this is the case, then flag canGetAndSetFMUstate must be true as well. |
| providesDirectionalDerivative | If true, the directional derivative of the equations can be computed with fmi2GetDirectionalDerivative(..) |

The flags have the following default values.

boolean: false

unsignedInt: 0

### Example XML Description File

When generating an FMU from the hypothetical model “MyLibrary.SpringMassDamper”, the XML file may have the following content:

**<?xml** version="1.0" encoding="UTF-8"?**>**

**<fmiModelDescription**

fmiVersion="2.0"

modelName="MyLibrary.SpringMassDamper"

guid="{8c4e810f-3df3-4a00-8276-176fa3c9f9e0}"

description="Rotational Spring Mass Damper System"

version="1.0"

generationDateAndTime="2011-09-23T16:57:33Z"

variableNamingConvention="structured"

numberOfEventIndicators="2"**>**

**<ModelExchange**

modelIdentifier="MyLibrary\_SpringMassDamper"**/>**

**<UnitDefinitions>**

**<Unit** name="rad"**>**

<**BaseUnit** rad="1"/>

**<DisplayUnit** name="deg" factor="57.2957795130823"**/>**

**</Unit>**

**<Unit** name="rad/s">

<**BaseUnit** s="-1" rad="1"/>

**</Unit>**

**<Unit** name="kg.m2">

<**BaseUnit** kg="1" m="2"/>

**</Unit>**

**<Unit** name="N.m"**>**

**<BaseUnit** kg="1" m="2" s="-2"/**>**

**</Unit>**

**</UnitDefinitions>**

**<TypeDefinitions>** **<SimpleType** name="Modelica.SIunits.Inertia"**>**

**<Real** quantity="MomentOfInertia" unit="kg.m2" min="0.0"**/>**

**</SimpleType>**

**<SimpleType** name="Modelica.SIunits.Torque"**>**

**<Real** quantity="Torque" unit="N.m"**/>**

**</SimpleType>**

**<SimpleType** name="Modelica.SIunits.AngularVelocity"**>**

**<Real** quantity="AngularVelocity" unit="rad/s"**/>**

**</SimpleType>**

**<SimpleType** name="Modelica.SIunits.Angle"**>**

**<Real** quantity="Angle" unit="rad"**/>**

**</SimpleType>**

**</TypeDefinitions>**

**<DefaultExperiment** startTime="0.0" stopTime="3.0" tolerance="0.0001"**/>**

**<ModelVariables>**

**<ScalarVariable**

name="inertia1.J"

valueReference="1073741824"

description="Moment of load inertia"

causality="parameter"

variability="fixed"**>**

**<Real** declaredType="Modelica.SIunits.Inertia" start="1"**/>**

**</ScalarVariable>** <!--index="1" -->

**<ScalarVariable**

name="torque.tau"

valueReference="536870912"

description="Accelerating torque acting at flange (= -flange.tau)"

causality="input"**>**

**<Real** declaredType="Modelica.SIunits.Torque" start="0" **/>**

**</ScalarVariable>** <!--index="2" -->

**<ScalarVariable**

name="inertia1.phi"

valueReference="805306368"

description="Absolute rotation angle of component"

causality="output"**>**

**<Real** declaredType="Modelica.SIunits.Angle" **/>**

**</ScalarVariable>** <!--index="3" -->

**<ScalarVariable**

name="inertia1.w"

valueReference="805306369"

description="Absolute angular velocity of component (= der(phi))"

causality="output"**>**

**<Real** declaredType="Modelica.SIunits.AngularVelocity" **/>**

**</ScalarVariable>** <!--index="4" -->

**<ScalarVariable** name="x[1]" valueReference="0" initial = "exact"> **<Real** start="0"/**>**

**</ScalarVariable>** <!--index="5" -->

**<ScalarVariable** name="x[2]" valueReference="1" initial = "exact"> **<Real** start="0"/**>**

**</ScalarVariable>** <!--index="6" -->

**<ScalarVariable** name="der(x[1])" valueReference="2">

**<Real** derivative="5"/**> </ScalarVariable>** <!--index="7" -->

**<ScalarVariable** name="der(x[2])" valueReference="3">

**<Real** derivative="6"/**> </ScalarVariable>** <!--index="8" -->

**</ModelVariables>**

**<ModelStructure>**

**<Outputs> <Unknown** index="3" **/> <Unknown** index="4" **/> </Outputs>**

**<Derivatives> <Unknown** index="7" **/> <Unknown** index="8" **/> </Derivatives>**

**<InitialUnknowns> <Unknown** index="3" **/> <Unknown** index="4" **/>**

**<Unknown** index="7" dependencies="5 2" **/>**

**<Unknown** index="8" dependencies="5 6" **/> </InitialUnknowns>**

**</ModelStructure>**

**</fmiModelDescription>**

# FMI for Co‑Simulation

This chapter defines the Functional Mock-up Interface (FMI) for the coupling of two or more simulation models in a co-simulation environment (*FMI for Co-Simulation*). Co-simulation is a rather general approach to the simulation of coupled technical systems and coupled physical phenomena in engineering with focus on instationary (time-dependent) problems.

FMI for Co-Simulation is designed both for coupling with subsystem models, which have been exported by their simulators together with its solvers as runnable code (Figure 7), and for coupling of simulation tools (*simulator coupling*, *tool coupling* (Figure 8 and Figure 9)).



Figure 7: Co-simulation with generated code on a single computer  
 (for simplicity shown for one slave only).



Figure 8: Co-simulation with tool coupling on a single computer  
 (for simplicity shown for one slave only).

In the tool coupling case the FMU implementation wraps the FMI function calls to API calls which are provided by the simulation tool (for example a COM or CORBA API). Additionally to the FMU the simulation tool is needed to run a co-simulation.

In its most general form, a tool coupling based co-simulation is implemented on distributed hardware with subsystems being handled by different computers with different OS (cluster computer, computer farm, computers at different locations). The data exchange and communication between the subsystems is typically done using one of the network communication technologies (for example, MPI, TCP/IP). The definition of this communication layer is not part of the FMI standard. However, distributed co‑simulation scenarios can be implemented using FMI as shown in Figure 9.



Figure 9: Distributed co-simulation infrastructure (for simplicity shown for one slave only).

The master has to implement the communication layer. Additional parameters for establishing the network communication (for example, identification of the remote computer, port numbers, user account) are to be set via the GUI of the master. These data are not transferred via the FMI API.

## Mathematical Description

### Basics

Co-simulation exploits the modular structure of coupled problems in all stages of the simulation process beginning with the separate model setup and preprocessing for the individual *subsystems* in different *simulation tools* (which can be powerful simulators as well as simple C programs). During time integration, the simulation is again performed independently for all subsystems restricting the data exchange between subsystems to discrete *communication points tci*. For simulator coupling, also the visualization and post-processing of simulation data is done individually for each subsystem in its own native simulation tool. In different contexts, the communication points *tci*, the *communication steps* *tci* → *tci+1* and the *communication step sizes* *hci* := *tci+1 - tci* are also known as sampling points (synchronization points), macro steps and sampling rates, respectively. The term “communication point” in FMI for Co-Simulation refers to the communication between subsystems in a co-simulation environment and should not be mixed with the output points for saving simulation results to file.

FMI for Co-Simulation provides an interface standard for the solution of time dependent *coupled systems* consisting of subsystems that are continuous in time (model components that are described by instationary differential equations) or time-discrete (model components that are described by difference equations such as discrete controllers). In a block representation of the coupled system, the subsystems are represented by blocks with (internal) *state variables* *x(t)* that are connected to other subsystems (blocks) of the coupled problem by *subsystem inputs* *u(t)* and *subsystem outputs* *y(t)*. In this framework, the physical connections between subsystems are represented by mathematical coupling conditions between the inputs *u(t)* and the outputs *y(t)* of all subsystems, *Kübler and Schiehlen (2000)*.

**y**

Co-Simulation Master

**v**

Solver

|  |  |
| --- | --- |
| *t* | time |
| **v** | all exposed variables |
| **p** | parameters of type Real, Integer, Boolean, String |
| **u** | inputs of type Real, Integer, Boolean, String |
| **y** | outputs of type Real, Integer, Boolean, String |
| **w** | local variables of the FMU |
| **xc** | continuous states (continuous between events) |
| **xd** | discrete states (constant between events) |
| **z** | (internal) event indicators |

Model

t0, **p, v0**

Co-Simulation Slave (FMU Instance)

**x**

*t*



**u**

Figure 10: Data flow at communication points.

For co-simulation two basic groups of functions have to be realized:

1. functions for the data exchange between subsystems
2. functions for algorithmic issues to synchronize the simulation of *all* subsystems and to proceed in communication steps *tci* → *tci+1* from initial time *tc0 := tstart* to end time *tcN := tstop*

In FMI for Co-Simulation, both functions are implemented in one software component, the co-simulation *master*. The data exchange between the subsystems (*slaves*) is handled via the master only. There is no direct communication between the slaves. The master functionality can be implemented by a special software tool (a separate simulation backplane) or by one of the involved simulation tools. In its most general form, the coupled system may be simulated in *nested* co-simulation environments and FMI for Co-Simulation applies to each level of the hierarchy.

FMI for Co-Simulation defines interface routines for the communication between the master and all slaves (subsystems) in a co-simulation environment. The most common master algorithm stops at each communication point *tci* the simulation (time integration) of all slaves, collects the outputs *y(tci)* from all subsystems, evaluates the subsystem inputs *u(tci)*, distributes these subsystem inputs to the slaves and continues the (co-)simulation with the next communication step *tci* → *tci+1 = tci+ hc* with fixed communication step size *hc*. In each slave, an appropriate solver is used to integrate one of the subsystems for a given communication step *tci* → *tci+1*. The most simple co-simulation algorithms approximate the (unknown) subsystem inputs *u(t), (t > tci)* by frozen data *u(tci)* for *tci* ≤ *t* < *tci+1*. FMI for Co-Simulation supports this classical brute force approach as well as more sophisticated master algorithms. FMI for Co-Simulation is designed to support a very general class of master algorithms but it does *not* define the master algorithm itself.

The ability of slaves to support more sophisticated master algorithms is characterized by a set of *capability flags* inside the XML description of the slave (see section 4.3.1). Typical examples are:

* the ability to handle variable communication step sizes *hci*,
* the ability to repeat a rejected communication step *tci* → *tci+1* with reduced communication step size,
* the ability to provide derivatives w.r.t. time of outputs to allow interpolation (section 4.2.1),
* or the ability to provide Jacobians.

FMI for Co-Simulation is restricted to slaves with the following properties:

1. All calculated values  are time dependent functions within an a priori defined time interval  (provided stopTimeDefined = fmi2True when calling fmi2SetupExperiment).
2. All calculations (simulations) are carried out with increasing timein general. The current time  is running step by step from  to . The algorithm of the slave may have the property to be able to repeat the simulation of parts of  or the whole time interval .
3. The slave can be given a time value , .
4. The slave is able to interrupt the simulation when is reached.
5. During the interrupted simulation the slave (and its individual solver) can receive values for inputs and send values of outputs .
6. Whenever the simulation in a slave is interrupted, a new time value , can be given to simulate the time subinterval 
7. The subinterval length  is the communication step size of the  communication step, . The communication step size has to be greater than zero.

FMI for Co-Simulation allows a co-simulation flow which starts with instantiation and initialization (all slaves are prepared for computation, the communication links are established), followed by simulation (the slaves are forced to simulate a communication step), and finishes with shutdown. The details of this flow are given in the state machine of the calling sequences from master to slave (see section 4.2.4).

### Mathematical Model

This section contains a formal mathematical model of a Co-Simulation FMU. The following fundamental assumptions are made:

The slave simulators are seen by the master simulator as purely sampled-data systems. Such a sampled-data system can be:

* A “real” sampled-data system (so a sampled discrete controller; the inputs and outputs can be of type Real, Integer, Boolean, String, or enumeration. Variables of this type are defined with variability = "discrete"; the smallest sample period as accessible by the outside of the FMU is defined by attribute stepSize in element DefaultExperiment).
* A hybrid ODE that is integrated between communication points (known as “sampled access to time continuous systems”) where internal events may occur and be handled, but events are not visible from the outside of the FMU. It is assumed here that all inputs and all outputs of this hybrid ODE are Real signals (defined with variability = "continuous").
* A combination of the systems above.

The communication between the master and a slave takes only place at a discrete set of time instants, called *communication points.*

An FMI Co-Simulation model is described by the following variables:

|  |  |
| --- | --- |
| *Variable* | *Description* |
|  | Independent variable time . (Variable defined with causality = "independent"). The i-th communication point is denoted as  The communication step size is denoted as |
|  | A vector of all exposed variables (all variables defined in element <ModelVariables>, see section 2.2.7). A subset of the variables is selected via a subscript. Example:  **v**initial=exact are variables defined with attribute initial = "exact", see section 2.2.7. These are independent parameters and start values of other variables, such as initial values for states, state derivatives or outputs. |
|  | Parameters that are constant during simulation. The symbol without a subscript references independent parameters (variables with causality = "parameter"). Dependent parameters (variables with causality = "calculatedParameter") are denoted as and tunable parameters (variables with causality = "parameter" and variability = "tunable") are denoted as . |
|  | Input variables. The values of these variables are defined outside of the model. Variables of this type are defined with attribute causality = "input". Whether the input is a discrete-time or continuous-time variable is defined via attribute variability = "discrete" or "continuous" (see section 2.2.7). |
|  | Output variables. The values of these variables are computed in the FMU and they are designed to be used in a model connection. So output variables might be used in the environment as input values to other FMUs or other submodels. Variables of this type are defined with attribute causality = "output". Whether the output is a discrete-time or continuous-time variable is defined via attribute variability = "discrete" or "continuous" (see section 2.2.7). |
|  | Local variables of the FMU that cannot be used for FMU connections. Variables of this type are defined with attribute causality = "local" (see section 2.2.7). |
| (*t*) | A vector of real continuous-time variables representing the continuous-time states.  For notational convenience, a continuous-time state is conceptually treated as a different type of variable as an output or a local variable for the mathematical description below. However, at a communication point, a continuous-time state is part of the outputs or the local variables of an FMU. |
|  | is a vector of (internal) discrete-time variables (of any type) representing the (internal) discrete states.  is the value of at the previous sample time instant, so .  Given the previous values of the discrete-time states, , at the actual time instant *t*, all other discrete-time variables, especially the discrete states , can be computed.  Discrete states are not visible in the interface of an FMU and are only introduced here to clarify the mathematical description. Formally, a discrete state is part of the outputs **y** or the local variables **w** of an FMU. |

When the transient simulation of the coupled system through co-simulation is completed, the sequence of evaluations is the following (here is the combined vector of continuous-time and discrete-time states, and is the combined vector of continuous-time and discrete-time outputs):

(4.1)

where and define the system behavior for the time interval , with

[*For the part of the co-simulation slave that is based on an ODE, a differential equation is solved between communication points:*

*In this case, the following relationship should hold (note the use of here):*

*This relation is in practice inexact due to using finite precision on machines and stopping iterations early. The slave simulators are responsible for implementing and , for example, to handle stiff differential equations as:*

]

Definition (4.1) is consistent with the definition of co-simulation by (Kübler, Schiehlen 2000).

* At the communication points, the master provides generalized inputs to the slave, which can be:
  + The current input variables of the subsystem (in other words, the input variables of the model contained in the slave simulator, in the sense of system-level simulation), along with some of their successive derivatives (in case of continuous-time variables), where *mido* stands for the model input derivative order.
  + Varying parameters , also known as tunable parameters
* The slave provides generalized outputs to the master, which are:
  + The current output variables of the subsystem (same remark as above), along with some of their successive derivatives (in case of continuous-time variables)
  + Observation variables and “calculated” varying parameters, along with directional derivatives estimated at (in case of continuous-time variables)
* Initialization: The slave being a sampled-data system, its internal states (which can be either continuous-time or discrete-time) need to be initialized at . This is performed through an auxiliary function [*this relationship is defined in the xml-file under <ModelStructure><InitialUnknowns>*]:

Computing the solution of an FMI Co-Simulation model means to split the solution process in two phases and in every phase different equations and solution methods are utilized. The phases can be categorized according to the following modes:

1. **Initialization Mode:** This mode is used to compute at the start time initial values for internal variables of the Co-Simulation slave, especially for continuous-time states, , and for the previous discrete-time states, , by utilizing extra equations not present in the other mode [*for example, equations to set all derivatives to zero, that is, to initialize in steady-state*]. If the slave is connected in loops with other models, iterations over the FMU equations are possible. Algebraic equations are solved in this mode.
2. **Step Mode:** This mode is used to compute the values of all (real) continuous-time and discrete-time variables at communication points by numerically solving ordinary differential, algebraic and discrete equations. If the slave is connected in loops with other models, no iterations over the FMU equations are possible.

[*Note that for a Co-Simulation FMU, no super dense time description is used at communication points.*]

The equations defined in Table 2 can be evaluated in the respective Mode. The following color coding is used in the table:

|  |  |
| --- | --- |
| grey | If a variable in an argument list is marked in grey, then this variable is not changing in this mode and just the last calculated value from the previous mode is internally used. For an input argument it is not allowed to call fmi2SetXXX. For an output argument, calling fmi2GetXXX on such a variable returns always the same value in this mode. |
| green | Functions marked in green are special functions to enter or leave a mode. |
| blue | Equations and functions marked in blue define the actual computations to be performed in the respective mode. |

Function fmi2SetXXX used in the table below, is an abbreviation for functions fmi2SetReal, fmi2SetBoolean, fmi2SetInteger and fmi2SetString respectively. Function fmi2GetXXX is an abbreviation for functions fmi2GetReal, fmi2GetBoolean, fmi2GetInteger and fmi2GetString respectively.

|  |  |
| --- | --- |
| **Equations** | **FMI functions** |
| ***Equations before Initialization Mode*** *(“instantiated” in state machine)* | |
| Set and set start value of independent variable | fmi2SetupExperiment |
| Set variables and that have a start value (initial = "exact" or "approx") | fmi2SetXXX |
| ***Equations during Initialization Mode*** *(“InitializationMode” in state machine)* | |
| Enter Initialization Mode at (activate initialization, discrete-time and continuous-time equations) | fmi2EnterInitializationMode |
| Set variables that have a start value with initial = "exact" (independent parameters and continuous-time states with start values  are included here) | fmi2SetXXX |
| Set continuous-time and discrete-time inputs and optionally the derivatives of continuous-time inputs | fmi2SetXXX fmi2SetRealInputDerivatives |
|  | fmi2GetXXX  fmi2GetDirectionalDerivative |
| Exit Initialization Mode (de-activate initialization equations) | fmi2ExitInitializationMode |
| ***Equations during Step Mode*** *(“stepComplete”, “stepInProgress” in state machine)* | |
| Set independent tunable parameters  (and do not set other parameters ) | fmi2SetXXX |
| Set continuous-time and discrete-time inputs and optionally the derivatives of continuous-time inputs | fmi2SetXXX fmi2SetRealInputDerivatives |
| is also a function of the internal variables | fmi2DoStep  fmi2GetXXX  fmi2GetRealOutputDerivatives  fmi2GetDirectionalDerivative |
| **Data types** | |
|  | |

Table 2: Mathematical description of an FMU for Co-Simulation.

[*Remark – Calling Sequences:*

*In the table above, for notational convenience in Initialization Mode one function call is defined to compute all output arguments from all inputs arguments. In reality, every scalar output argument is computed by one* fmi2GetXXX *function call.*

*In Step Mode the input arguments to are defined by calls to* fmi2SetXXX *and* fmi2SetRealInputDerivatives *functions. The variables computed by can be inquired by* fmi2GetXXX *function calls.*]

## FMI Application Programming Interface

This section contains the interface description to access the in/output data and status information of a co-simulation slave from a C program.

### Transfer of Input / Output Values and Parameters

Input and output variables and variables are transferred via the fmi2GetXXX and fmi2SetXXX functions, defined in section 2.1.7.

In order to enable the slave to interpolate the continuous real inputs between communication steps, the derivatives of the inputs with respect to time can be provided. Also, higher derivatives can be set to allow higher order interpolation. Whether a slave is able to interpolate and therefore needs this information is provided by the capability attribute canInterpolateInputs.

|  |  |
| --- | --- |
| fmi2Status fmi2SetRealInputDerivatives(fmi2Component c,   **const** fmi2ValueReference vr[], **sizet** nvr,  **const** fmi2Integer order[],  **const** fmi2Real value[]); | |
|  | Sets the n-th time derivative of real input variables. Argument vr is a vector of value references that define the variables whose derivatives shall be set. The array order contains the orders of the respective derivative (1 means the first derivative, 0, is not allowed). Argument value is a vector with the values of the derivatives. nvr is the dimension of the vectors.  Different input variables may have different interpolation order.  Restrictions on using the function are the same as for the fmi2SetReal function. |

Inputs and their derivatives are set with respect to the beginning of a communication time step.

To allow interpolation/approximation of the real output variables between communication steps (if they are used as inputs for other slaves), the derivatives of the outputs with respect to time can be read. Whether the slave is able to provide the derivatives of outputs is given by the unsigned integer capability flag MaxOutputDerivativeOrder; it delivers the maximum order of the output derivative. If the actual order is lower (because the order of integration algorithm is low), the retrieved value is 0.

Example: If the internal polynomial is of order 1 and the master inquires the second derivative of an output, the slave will return zero.

The derivatives can be retrieved by:

|  |  |
| --- | --- |
| fmi2Status fmi2GetRealOutputDerivatives (fmi2Component c,   **const** fmi2ValueReference vr[], **sizet** nvr,  **const** fmi2Integer order[],  fmi2Real value[]); | |
|  | Retrieves the n-th derivative of output values. Argument vr is a vector of nvr value references that define the variables whose derivatives shall be retrieved. The array order contains the order of the respective derivative (1 means the first derivative, 0 is not allowed). Argument value is a vector with the actual values of the derivatives.  Restrictions on using the function are the same as for the fmi2GetReal function. |

The returned outputs correspond to the current slave time. For example, after a successful fmi2DoStep(..) the returned values are related to the end of the communication time step.

This standard supports polynomial interpolation and extrapolation as well as more sophisticated signal extrapolation schemes like rational extrapolation.

### Computation

The computation of time steps is controlled by the following function.

|  |  |
| --- | --- |
| fmi2Status fmi2DoStep(fmi2Component c,   fmi2Real currentCommunicationPoint,  fmi2Real communicationStepSize,   fmi2Boolean noSetFMUStatePriorToCurrentPoint); | |
|  | The computation of a time step is started.  Argument currentCommunicationPoint is the current communication point of the master () and argument communicationStepSize is the communication step size (). The latter must be . The slave must integrate until time instant. [*The calling environment defines the communication points and* fmi2DoStep *must synchronize to these points by always integrating exactly to . It is up to fmi2DoStep how to achieve this.*] *At the first call to fmiDoStep after fmi2ExitInitializationMode was called currentCommunicationPoint must be equal to startTime as set with fmi2SetupExperiment.* [*Formally, argument* currentCommunicationPoint *is not needed. It is present in order to handle a mismatch between the master and the FMU state of the slave: The currentCommunicationPoint and the FMU state of the slaves defined by former fmi2DoStep or fmi2SetFMUState calls have to be consistent with respect to each other. For example, if the slave does not use the update formula for the independent variable as required above, (using argument currentCommunicationPoint* of *fmi2DoStep) but uses internally an own update formula, such as then the slave could use as time increment (instead of ,) to avoid a mismatch between the master time and the slave internal time for large i.*]  Argument noSetFMUStatePriorToCurrentPoint is fmi2True if fmi2SetFMUState will no longer be called for time instants prior to currentCommunicationPoint in this simulation run [*the slave can use this flag to flush a result buffer*].  The function returns:  fmi2OK – if the communication step was computed successfully until its end.  fmi2Discard – if the slave computed successfully only a subinterval of the communication step. The master can call the appropriate fmi2GetXXXStatus functions to get further information. If possible, the master should retry the simulation with a shorter communication step size. [*Redoing a step is only possible if the FMU state has been recorded at the beginning of the current (failed) step with fmi2GetFMUState. Redoing a step is performed by calling fmi2SetFMUState and afterwards calling fmi2DoStep with the new communicationStepSize. Note that it is not possible to change currentCommunicationPoint in such a call.*]  fmi2Error – the communication step could not be carried out at all. The master can try to repeat the step with other input values and/or a different communication step size in the same way as described in the fmi2Discard case above.  fmi2Fatal – if an error occurred which corrupted the FMU irreparably. *[The master should stop the simulation run immediatlely.]* See section 2.1.3 for details.  fmi2Pending – this status is returned if the slave executes the function asynchronously. That means the slave starts the computation but returns immediately. The master has to call fmi2GetStatus(...,fmi2DoStep,...) to find out if the slave is done. An alternative is to wait until the callback function fmi2StepFinished is called by the slave. fmi2CancelStep can be called to cancel the current computation. It is not allowed to call any other function during a pending fmi2DoStep. |
| fmi2Status fmi2CancelStep(fmi2Component c); | |
|  | Can be called if fmi2DoStep returned fmi2Pending in order to stop the current asynchronous execution. The master calls this function if, for example, the co-simulation run is stopped by the user or one of the slaves. Afterwards only calls to fmi2Reset, fmi2FreeInstance, or fmi2SetFMUstate are valid to exit the step Canceled state. Refer to section 4.2.4 for all other valid functions in this state. |

It depends on the capabilities of the slave which parameter constellations and calling sequences are allowed (see 4.3.1).

### Retrieving Status Information from the Slave

Status information is retrieved from the slave by the following functions:

|  |  |
| --- | --- |
| fmi2Status fmi2GetStatus (fmi2Component c, **const** fmi2StatusKind s,  fmi2Status\* value);  fmi2Status fmi2GetRealStatus (fmi2Component c, **const** fmi2StatusKind s,fmi2Real\* value);  fmi2Status fmi2GetIntegerStatus(fmi2Component c, **const** fmi2StatusKind s,  fmi2Integer\* value);  fmi2Status fmi2GetBooleanStatus(fmi2Component c, **const** fmi2StatusKind s,  fmi2Boolean\* value);  fmi2Status fmi2GetStringStatus (fmi2Component c, **const** fmi2StatusKind s,  fmi2String\* value); | |
|  | Informs the master about the actual status of the simulation run. Which status information is to be returned is specified by the argument fmi2StatusKind. It depends on the capabilities of the slave which status information can be given by the slave (see 4.3.1). If a status is required which cannot be retrieved by the slave it returns fmi2Discard. |
| **typedef** **enum** {fmi2DoStepStatus,  fmi2PendingStatus,  fmi2LastSuccessfulTime,  fmi2Terminated  } fmi2StatusKind; | |
|  | Defines which status is inquired. |

The following status information can be retrieved from a slave:

|  |  |  |
| --- | --- | --- |
| Status | *Type of retrieved value* | *Description* |
| fmi2DoStepStatus | fmi2Status | Can be called when the fmi2DoStep function returned fmi2Pending. The function delivers fmi2Pending if the computation is not finished. Otherwise the function returns the result of the asynchronously executed fmi2DoStep call. |
| fmi2PendingStatus | fmi2String | Can be called when the fmi2DoStep function returned fmi2Pending. The function delivers a string which informs about the status of the currently running asynchronous fmi2DoStep computation. |
| fmi2LastSuccessfulTime | fmi2Real | Returns the end time of the last successfully completed communication step. Can be called after fmi2DoStep(..) returned fmi2Discard. |
| fmi2Terminated | fmi2Boolean | Returns fmi2True, if the slave wants to terminate the simulation. Can be called after fmi2DoStep(..) returned fmi2Discard. Use fmi2LastSuccessfulTime to determine the time instant at which the slave terminated. |

### State Machine of Calling Sequence from Master to Slave

The following state machine defines the supported calling sequences.



Figure 11: Calling sequence of Co-Simulation C functions in form of an UML 2.0 state machine.

Each state of the state machine corresponds to a certain phase of a simulation as follows:

**instantiated**:  
In this state, start and guess values (= variables that have initial = "exact" or "approx" and variability ≠ "constant") can be set, this does not include inputs as they do not have an initial attribute but one can set input derivatives with the function fmi2SetRealInputDerivatives.

**Initialization Mode:**In this state, equations are active to determine all outputs (and optionally other variables exposed by the exporting tool). The variables that can be retrieved by fmi2GetXXX calls are (1) defined in the xml file under <ModelStructure><InitialUnknowns>, and (2) variables with causality = ″output″. Variables with initial = ″exact″ and variability ≠ "constant", as well as variables with causality = ″input″ can be set.

**slaveInitialized**:  
In this state, the slave is initialized and the co-simulation computation is performed. The calculation until the next communication point is performed with function “fmi2DoStep”. Depending on the return value, the slave is in a different state (step complete, step failed, step canceled).

**terminated**:  
In this state, the solution at the final time of the simulation can be retrieved.

Note that in Initialization Mode input variables can be set with fmi2SetXXX and output variables can be retrieved with fmi2GetXXX interchangeably according to the model structure defined under element <ModelStructure><InitialUnknowns> in the xml-file. [*For example, if one output* y1 *depends on two inputs* u1*,* u2*, then these two inputs must be set, before* y1 *can be retrieved. If additionally an output* y2 *depends on an input* u3*, then* u3 *can be set and* y2 *can be retrieved afterwards. As a result, artificial or “real” algebraic loops over connected FMUs in Initialization Mode can be handled by using appropriate numerical algorithms.*]

There is the additional restriction in “slaveInitialized” state that it is not allowed to call fmi2GetXXX functions after fmi2SetXXX functions without an fmi2DoStep call in between. [*The reason is to avoid different interpretations of the caching, since contrary to FMI for Model Exchange, fmi2DoStep will perform the actual calculation instead of* fmi2GetXXX*, and therefore, dummy algebraic loops at communication points cannot be handeled by an appropriate sequence of* fmi2GetXXX *and* fmi2SetXXX *calls as for ModelExchange.*

*Examples:*

|  |  |
| --- | --- |
| *Correct calling sequence* | *Wrong calling sequence* |
| *fmi2SetXXX on inputs*  *fmi2DoStep*  *fmi2GetXXX on outputs*  *fmi2SetXXX on inputs*  *fmi2DoStep*  *fmi2GetXXX on outputs* | *fmi2SetXXX on inputs*  *fmi2DoStep*  *fmi2GetXXX on outputs*  *fmi2SetXXX on inputs*  *fmi2GetXXX on outputs // not allowed*  *fmi2DoStep*  *fmi2GetXXX on outputs* |

]

The allowed function calls in the respective states are summarized in the following table (functions marked in “light blue” are only available for “Co-Simulation”, the other functions are available both for “Model Exchange” and “Co-Simulation”):

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **FMI 2.0 forCo-Simulation** | | | | | | | | | |  |  |
| **Function** | start, end | instantiated | Initialization Mode | stepComplete | stepInProgress | stepFailed | stepCanceled | terminated | error | fatal |  |  |
| fmi2GetTypesPlatform | x | x | x | x | x | x | x | x | x |  |  |  |
| fmi2GetVersion | x | x | x | x | x | x | x | x | x |  |  |  |
| fmi2SetDebugLogging |  | x | x | x | x | x | x | x | x |  |  |  |
| fmi2Instantiate | x |  |  |  |  |  |  |  |  |  |  |  |
| fmi2FreeInstance |  | x | x | x |  | x | x | x | x |  |  |  |
| fmi2SetupExperiment |  | x |  |  |  |  |  |  |  |  |  |  |
| fmi2EnterInitializationMode |  | x |  |  |  |  |  |  |  |  |  |  |
| fmi2ExitInitializationMode |  |  | x |  |  |  |  |  |  |  |  |  |
| fmi2Terminate |  |  |  | x |  | x |  |  |  |  |  |  |
| fmi2Reset |  | x | x | x |  | x | x | x | x |  |  |  |
| fmi2GetReal |  |  | 2 | x |  | 8 | 7 | x | 7 |  |  |  |
| fmi2GetInteger |  |  | 2 | x |  | 8 | 7 | x | 7 |  |  |  |
| fmi2GetBoolean |  |  | 2 | x |  | 8 | 7 | x | 7 |  |  |  |
| fmi2GetString |  |  | 2 | x |  | 8 | 7 | x | 7 |  |  |  |
| fmi2SetReal |  | 1 | 3 | 6 |  |  |  |  |  |  |  |  |
| fmi2SetInteger |  | 1 | 3 | 6 |  |  |  |  |  |  |  |  |
| fmi2SetBoolean |  | 1 | 3 | 6 |  |  |  |  |  |  |  |  |
| fmi2SetString |  | 1 | 3 | 6 |  |  |  |  |  |  |  |  |
| fmi2GetFMUstate |  | x | x | x |  | 8 | 7 | x | 7 |  |  |  |
| fmi2SetFMUstate |  | x | x | x |  | x | x | x | x |  |  |  |
| fmi2FreeFMUstate |  | x | x | x |  | x | x | x | x |  |  |  |
| fmi2SerializedFMUstateSize |  | x | x | x |  | x | x | x | x |  |  |  |
| fmi2SerializeFMUstate |  | x | x | x |  | x | x | x | x |  |  |  |
| fmi2DeSerializeFMUstate |  | x | x | x |  | x | x | x | x |  |  |  |
| fmi2GetDirectionalDerivative |  |  | x | x |  | 8 | 7 | x | 7 |  |  |  |
| fmi2SetRealInputDerivatives |  | x | x | x |  |  |  |  |  |  |  |  |
| fmi2GetRealOutputDerivatives |  |  |  | x |  | 8 | x | x | 7 |  |  |  |
| fmi2DoStep |  |  |  | x |  |  |  |  |  |  |  |  |
| fmi2CancelStep |  |  |  |  | x |  |  |  |  |  |  |  |
| fmi2GetStatus |  |  |  | x | x | x |  | x |  |  |  |  |
| fmi2GetRealStatus |  |  |  | x | x | x |  | x |  |  |  |  |
| fmi2GetIntegerStatus |  |  |  | x | x | x |  | x |  |  |  |  |
| fmi2GetBooleanStatus |  |  |  | x | x | x |  | x |  |  |  |  |
| fmi2GetStringStatus |  |  |  | x | x | x |  | x |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |

**x** means: call is allowed in the corresponding state

**number** means: call is allowed if the indicated condition holds:

**1** for a variable with variability ≠ "constant" that has initial = "exact" or "approx"

**2** for a variable with causality = "output" or variables listed under <ModelStructure><InitalUnkowns>

**3** for a variable with variability ≠ "constant"  
 that has initial = "exact", or causality = "input"

**6** for a variable with causality = "input" or  
 (causality = "parameter" and variability = "tunable")

**7** always, but retrieved values are usable for debugging only

**8** always, but if status is other than fmi2Terminated, retrieved values are useable for debugging only

### Pseudocode Example

In the following example, the usage of the FMI functions is sketched in order to clarify the typical calling sequence of the functions in a simulation environment. The example is given in a mix of pseudocode and C Code, in order to keep it small and understandable. We consider two slaves, where both have one continuous real input and one continuous real output which are connected in the following way:



Figure 12 Connection graph of the slaves.

We assume no algebraic dependency between input and output of each slave. The code demonstrates the simplest master algorithm as shown in section 4.1:

* Constant communication step size.
* No repeating of communication steps.
* The slaves do not support asynchronous execution of fmi2DoStep.

The error handling is implemented in a very rudimentary way.

|  |
| --- |
| //////////////////////////  //Initialization sub-phase  //Set callback functions,  fmi2CallbackFunctions cbf;  cbf.logger = loggerFunction; //logger function  cbf.allocateMemory = calloc;  cbf.freeMemory = free;  cbf.stepFinished = NULL; //synchronous execution  cbf.componentEnvironment = NULL;  //Instantiate both slaves  fmi2Component s1 = s1\_fmi2Instantiate("Tool1" , fmi2CoSimulation, GUID1, "",  fmi2False, fmi2False, &cbf, fmi2True);  fmi2Component s2 = s2\_fmi2Instantiate("Tool2" , fmi2CoSimulation, GUID2, "",  fmi2False, fmi2False, &cbf, fmi2True);  if ((s1 == NULL) || (s2 == NULL))  return FAILURE;  // Start and stop time  startTime = 0;  stopTime = 10;  //communication step size  h = 0.01;  // set all variable start values (of "ScalarVariable / <type> / start")  s1\_fmi2SetReal/Integer/Boolean/String(s1, ...);  s2\_fmi2SetReal/Integer/Boolean/String(s2, ...);  //Initialize slaves  s1\_fmi2SetupExperiment(s1, fmi2False, 0.0, startTime, fmi2True, stopTime);  s2\_fmi2SetupExperiment(s1, fmi2False, 0.0, startTime, fmi2True, stopTime);  s1\_fmi2EnterInitializationMode(s1);  s2\_fmi2EnterInitializationMode(s2);  // set the input values at time = startTime  s1\_fmi2SetReal/Integer/Boolean/String(s1, ...);  s2\_fmi2SetReal/Integer/Boolean/String(s2, ...);  s1\_fmi2ExitInitializationMode(s1);  s2\_fmi2ExitInitializationMode(s2);  //////////////////////////  //Simulation sub-phase  tc = startTime; //Current master time  while ((tc < stopTime) && (status == fmi2OK))  {  //retrieve outputs  s1\_fmi2GetReal(s1, ..., 1, &y1);  s2\_fmi2GetReal(s2, ..., 1, &y2);  //set inputs  s1\_fmi2SetReal(s1, ..., 1, &y2);  s2\_fmi2SetReal(s2, ..., 1, &y1);  //call slave s1 and check status  status = s1\_fmi2DoStep(s1, tc, h, fmi2True);  switch (status) {  case fmi2Discard:  fmi2GetBooleanStatus(s1, fmi2Terminated, &boolVal);  if (boolVal == fmi2True)  printf("Slave s1 wants to terminate simulation.");  case fmi2Error:  case fmi2Fatal:  terminateSimulation = true;  break;  }  if (terminateSimulation)  break;  //call slave s2 and check status as above  status = s2\_fmi2DoStep(s2, tc, h, fmi2True);  ...  //increment master time  tc += h;  }  //////////////////////////  //Shutdown sub-phase  if ((status != fmi2Error) && (status != fmi2Fatal))  {  s1\_fmi2Terminate(s1);  s2\_fmi2Terminate(s2);  }  if (status != fmi2Fatal)  {  s1\_fmi2FreeInstance(s1);  s2\_fmi2FreeInstance(s2);  } |

## FMI Description Schema

This is defined in section 2.2. Additionally, the co-simulation specific element “Implementation” is defined in the next section.

### Co‑Simulation FMU (CoSimulation)

If the XML file defines an FMU for Co-Simulation, element “CoSimulation” must be present. It is defined as:





These attributes have the following meaning (all attributes are optional with exception of “modelIdentifier”):

|  |  |
| --- | --- |
| Attribute Name | *Description* |
| modelIdentifier | Short class name according to C syntax, for example, “A\_B\_C”. Used as prefix for FMI functions if the functions are provided in C source code or in static libraries, but not if the functions are provided by a DLL/SharedObject. modelIdentifier is also used as name of the static library or DLL/SharedObject. See also section 2.1.1. |
| needsExecutionTool | If true, a tool is needed to execute the model. The FMU just contains the communication to this tool (see Figure 8). [*Typically, this information is only utilized for information purposes. For example, a co‑simulation master can inform the user that a tool has to be available on the computer where the slave is instantiated. The name of the tool can be taken from attribute* generationTool *of* fmiModelDescription.] |
| canHandleVariableCommunicationStepSize | The slave can handle variable communication step size. The communication step size (parameter communicationStepSize of fmi2DoStep(..) ) has not to be constant for each call. |
| canInterpolateInputs | The slave is able to interpolate continuous inputs. Calling of fmi2SetRealInputDerivatives(..) has an effect for the slave. |
| maxOutputDerivativeOrder | The slave is able to provide derivatives of outputs with maximum order. Calling of fmi2GetRealOutputDerivatives(..) is allowed up to the order defined by maxOutputDerivativeOrder. |
| canRunAsynchronuously | This flag describes the ability to carry out the fmi2DoStep(..) call asynchronously. |
| canBeInstantiatedOnlyOncePerProcess | This flag indicates cases (especially for embedded code), where only one instance per FMU is possible. (Multiple instantiation is default = false; if multiple instances are needed, the FMUs must be instantiated in different processes.) |
| canNotUseMemoryManagementFunctions | If true, the slave uses its own functions for memory allocation and freeing only. The callback functions allocateMemory and freeMemory given in fmi2Instantiate are ignored. |
| canGetAndSetFMUstate | If true, the environment can inquire the internal FMU state and restore it. That is, fmi2GetFMUstate, fmi2SetFMUstate, and fmi2FreeFMUstate are supported by the FMU. |
| canSerializeFMUstate | If true, the environment can serialize the internal FMU state, in other words, fmi2SerializedFMUstateSize, fmi2SerializeFMUstate, fmi2DeSerializeFMUstate are supported by the FMU. If this is the case, then flag canGetAndSetFMUstate must be true as well. |
| providesDirectionalDerivative | If true, the directional derivative of the equations at communication points can be computed with fmi2GetDirectionalDerivative(..) |

The flags have the following default values.

boolean: false

unsignedInt: 0

Note that if needsExecutionTool = true, then it is required that the original tool is available to be executed in co-simulation mode. If needsExecutionTool = false, the slave is completely contained inside the FMU in source code or binary format (DLL/SharedObject).

### Example XML Description File

The example below is the same one as shown in section 3.3.2 for a ModelExchange FMU. The only difference is the replacement of element ModelExchange by element CoSimulation (with additional attributes) and the removal of local variables, which are associated with continuous states and their derivatives. The XML file may have the following content:

**<?xml** version="1.0" encoding="UTF-8"?**>**

**<fmiModelDescription**

fmiVersion="2.0"

modelName="MyLibrary.SpringMassDamper"

guid="{8c4e810f-3df3-4a00-8276-176fa3c9f9e0}"

description="Rotational Spring Mass Damper System"

version="1.0"

generationDateAndTime="2011-09-23T16:57:33Z"

variableNamingConvention="structured"**>**

**<CoSimulation**

modelIdentifier="MyLibrary\_SpringMassDamper"

canHandleVariableCommunicationStepSize="true"

canInterpolateInputs="true"**/>**

**<UnitDefinitions>**

**<Unit** name="rad"**>**

<**BaseUnit** rad="1"/>

**<DisplayUnit** name="deg" factor="57.2957795130823"**/>**

**</Unit>**

**<Unit** name="rad/s">

<**BaseUnit** s="-1" rad="1"/>

**</Unit>**

**<Unit** name="kg.m2">

<**BaseUnit** kg="1" m="2"/>

**</Unit>**

**<Unit** name="N.m">

<BaseUnit kg="1" m="2" s="-2"/>

**</Unit>**

**</UnitDefinitions>**

**<TypeDefinitions>**

**<SimpleType** name="Modelica.SIunits.Inertia"**>**

**<Real** quantity="MomentOfInertia" unit="kg.m2" min="0.0"**/> </SimpleType>**

**<SimpleType** name="Modelica.SIunits.Torque"**>**

**<Real** quantity="Torque" unit="N.m"**/>** **</SimpleType>**

**<SimpleType** name="Modelica.SIunits.AngularVelocity"**>**

**<Real** quantity="AngularVelocity" unit="rad/s"**/>** **</SimpleType>**

**<SimpleType** name="Modelica.SIunits.Angle"**>**

**<Real** quantity="Angle" unit="rad"**/>** **</SimpleType>**

**</TypeDefinitions>**

**<DefaultExperiment** startTime="0.0" stopTime="3.0" tolerance="0.0001"**/>**

**<ModelVariables>**

**<ScalarVariable**

name="inertia1.J"

valueReference="1073741824"

description="Moment of load inertia"

causality="parameter"

variability="fixed"**>**

**<Real** declaredType="Modelica.SIunits.Inertia" start="1"**/>**

**</ScalarVariable>**

**<ScalarVariable**

name="torque.tau"

valueReference="536870912"

description="Accelerating torque acting at flange (= -flange.tau)"

causality="input"**>**

**<Real** declaredType="Modelica.SIunits.Torque" start="0"**/>**

**</ScalarVariable>**

**<ScalarVariable**

name="inertia1.phi"

valueReference="805306368"

description="Absolute rotation angle of component"

causality="output"**>**

**<Real** declaredType="Modelica.SIunits.Angle" **/>**

**</ScalarVariable>**

**<ScalarVariable**

name="inertia1.w"

valueReference="805306369"

description="Absolute angular velocity of component (= der(phi))"

causality="output"**>**

**<Real** declaredType="Modelica.SIunits.AngularVelocity" **/>**

**</ScalarVariable>**

**</ModelVariables>**

**<ModelStructure>**

**<Outputs>**

**<Unknown** index="3"**/>**

**<Unknown** index="4"**/>**

**</Outputs>**

**<InitialUnknowns>**

**<Unknown** index="3"**/>**

**<Unknown** index="4"**/>**

**</InitialUnknowns>**

**</ModelStructure>**

<**/fmiModelDescription**>

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1. FMI Revision History

This appendix describes the history of the FMI design and its contributors. The current version of this document is available from <https://fmi-standard.org/downloads/>.

The Functional Mock-up Interface development was initiated and organized by Daimler AG (from Bernd Relovsky and others) as subproject inside the [ITEA2](http://www.itea2.org/) MODELISAR project.

The development of versions 1.0 and 2.0 was performed within WP200 of MODELISAR, organized by the WP200 work package leader Dietmar Neumerkel from Daimler.

* 1. Version 1.0 – FMI for Model Exchange

Version 1.0 of FMI for Model Exchange was released on Jan. 26, 2010.

The subgroup “FMI for Model Exchange” was headed by Martin Otter (DLR-RM). The essential part of the design of this version was performed by (alphabetical list):

Torsten Blochwitz, ITI, Germany

Hilding Elmqvist, Dassault Systèmes, Sweden

Andreas Junghanns, QTronic, Germany

Jakob Mauss, QTronic, Germany

Hans Olsson, Dassault Systèmes, Sweden

Martin Otter, DLR-RM, Germany.

This version was evaluated with prototypes implemented for (alphabetical list):

Dymola by Peter Nilsson, Dan Henriksson, Carl Fredrik Abelson, and Sven Erik Mattson,   
 Dassault Systèmes,

JModelica.org by Tove Bergdahl, Modelon AB,

Silver by Andreas Junghanns, and Jakob Mauss, QTronic.

These prototypes have been used to refine the design of “FMI for Model Exchange”.

The following MODELISAR partners participated at FMI design meetings and contributed to the discussion (alphabetical list):

Ingrid Bausch-Gall, Bausch-Gall GmbH, Munich, Germany

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Andreas Junghanns, QTronic GmbH, Berlin, Germany

Rainer Keppler, SIMPACK AG, Gilching, Germany

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Thomas Neidhold, ITI GmbH, Dresden, Germany

Dietmar Neumerkel, Daimler AG, Stuttgart, Germany

Peter Nilsson, Dassault Systèmes, Lund, Sweden

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Antoine Viel, LMS International (Imagine), Roanne, France

Daniel Weil, Dassault Systèmes, Grenoble, France

The following people outside of the MODELISAR consortium contributed with comments:

Johan Akesson, Lund University, Lund, Sweden  
Joel Andersson, KU Leuven, The Netherlands  
Roberto Parrotto, Politecnico di Milano, Italy

* 1. Version 1.0 – FMI for Co-Simulation

Version 1.0 of FMI for Co-Simulation was released on Oct. 10, 2010.

FMI for Co-Simulation was developed in three subgroups: “Solver Coupling” headed by Martin Arnold (University Halle) and Torsten Blochwitz (ITI), “Tool Coupling” headed by Jörg-Volker Peetz (Fraunhofer SCAI), and “Control Logic” headed by Manuel Monteiro (Atego). The essential part of the design of this version was performed by (alphabetical list):

Martin Arnold, University Halle, Germany

Constanze Bausch, Atego Systems GmbH, Wolfsburg, Germany

Torsten Blochwitz, ITI GmbH, Dresden, Germany

Christoph Clauß, Fraunhofer IIS EAS, Dresden, Germany

Manuel Monteiro, Atego Systems GmbH, Wolfsburg, Germany

Thomas Neidhold, ITI GmbH, Dresden, Germany

Jörg-Volker Peetz, Fraunhofer SCAI, St. Augustin, Germany

Susann Wolf, Fraunhofer IIS EAS, Dresden, Germany

This version was evaluated with prototypes implemented for (alphabetical list):

SimulationX by Torsten Blochwitz and Thomas Neidhold (ITI GmbH),

Master algorithms by Christoph Clauß (Fraunhofer IIS EAS)

The following MODELISAR partners participated at FMI design meetings and contributed to the discussion (alphabetical list):

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Constanze Bausch, Atego Systems GmbH, Wolfsburg, Germany  
Torsten Blochwitz, ITI GmbH, Dresden, Germany  
Christoph Clauß, Fraunhofer IIS EAS, Dresden, Germany  
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Dietmar Neumerkel, Daimler AG, Böblingen, Germany  
Martin Otter, DLR, Oberpfaffenhofen, Germany  
Jörg-Volker Peetz, Fraunhofer SCAI, St. Augustin, Germany  
Tom Schierz, University Halle, Germany

Klaus Wolf, Fraunhofer SCAI, St. Augustin, Germany

* 1. Version 2.0 – FMI for Model Exchange and Co-Simulation

FMI 2.0 for Model Exchange and Co-Simulation was released on July 25, 2014.

* + 1. Overview

This section gives an overview about the changes with respect to versions 1.0 for Model Exchange and 1.0 for Co-Simulation:

* FMI 2.0 is not backwards compatible to FMI 1.0.
* The documents, schema and header files for Model Exchange and for Co-Simulation have been merged. Due to the merging, some conflicts had to be resolved leading to some non-backwards compatible changes with respect to FMI 1.0.
* Parameters can be declared to be “tunable” in the FMU, in other words, during simulation these parameters can be changed (if supported by the simulation environment).
* When enabling logging, log categories to be logged can be defined, so that the FMU only needs to generate logs of the defined categories (in FMI 1.0, logs had to be generated for all log categories and they had to be filtered afterwards). Log categories that are supported by an FMU can be optionally defined in the XML file so that a simulation environment can provide them to the user for selection.
* In order that tools can more simply support importing both FMI 1.0 and 2.0, all file and function names of FMI 2.0 start with “fmi2”, whereas they start with “fmi” for FMI 1.0.
* FMI function names are no longer prefixed with the “modelIdentifier” if used in a DLL/sharedObject. As a result, FMUs that need a tool can use a generic communication DLL, and the loading of DLLs is no longer FMU dependent.
* The different modes of an FMU are now clearly signaled with respective function calls (fmi2EnterInitializationMode, fmi2EnterEventMode, fmi2EnterContinuousTimeMode).
* The interfaces have been redesigned, in order that algebraic loops over connected FMUs with Real, Integer, or Boolean unknowns can now be handled reasonably not only in Continuous Time Mode, but also in Initialization and Event Mode. In FMI 1.0, algebraic loops in Initialization and Even Mode could not be handled.
* The termination of every global event iteration over connected FMUs must be reported by a new function call (fmi2EnterContinuousTimeMode).
* The unit definitions have been improved: The tool-specific unit-name can optionally be expressed as function of the 7 SI base units and the SI derived unit “rad”. It is then possible to check units when FMUs are connected together (without standardizing unit names), or to convert variable values that are provided in different units (for the same physical quantity).
* Enumerations have an arbitrary (but unique) mapping to integers (in FMI 1.0, the mapping was automatically to 1,2,3,...).
* The alias/negatedAlias variable definitions have been removed, to simplify the interface: If variables of the same base type (like fmi2Real) have the same valueReference, they have identical values. A simulation environment may ignore this completely (this was not possible in FMI 1.0), or can utilize this information to more efficiently store results on file.
* When instantiating an FMU, the absolute path to the FMU resource directory is now reported also in Model Exchange, in order that the FMU can read all of its resources (for example, maps, tables, ...) independently of the “current directory” of the simulation environment where the FMU is used.
* An ordering is defined for input, output, and state variables in the XML file of an FMU, in order for this order to be defined in the FMU, and not be (arbitrarily) selected by the simulation environment. This is essential, for example, when linearizing an FMU, or when providing “sparsity” information (see below).
* Several optional features have been added:
  + The complete FMU state can be saved, restored, and serialized to a byte vector (that can be stored on file). As a result, a simulation (both for Model Exchange and for Co-Simulation) can be restarted from a saved FMU state. Rejecting steps for variable step-size Co-Simulation master algorithms is now performed with this feature (instead of the less powerful method of FMI 1.0).
  + The dependency of state derivatives and of output variables from inputs and states can be defined in the XML file, in other words the sparsity pattern for Jacobians can be defined. This allows simulating stiff FMUs with many states (> 1000 states) since sparse matrix methods can be utilized in the numerical integration method. Furthermore, it can be stated whether this dependency is linear (this allows to transform nonlinear algebraic equation systems into linear equation systems when connecting FMUs).
  + Directional derivatives can be computed for derivatives of continuous-time states and for outputs. This is useful when partial derivatives of connected FMUs must be computed. If the exported FMU performs this computation analytically, then all numerical algorithms based on these partial derivatives (for example, the numerical integration method or nonlinear algebraic solvers) are more efficient and more reliable.
  + Every scalar variable definition can have an additional “annotation” data structure that is arbitrary (“any” element in XML). A tool vendor can store tool-dependent information here (that other tools can ignore), for example, to store the graphical layout of parameter menus. The VendorAnnotations element was also generalized from (name, value) pairs to any XML data structure.
* Many smaller improvements have been included, due to the experience in using FMI 1.0 (for example, the causality/variability attributes have been changed and more clearly defined, the fmi2ModelFunctions.h header has been split into two header files (one for the function signature, and one for the function names), in order that the header files can be directly used both for DLLs and for source code distribution.
  + 1. Main changes

This section gives the details about the changes with respect to versions 1.0 for Model Exchange and 1.0 for Co-Simulation:

In this version, the documents of version 1.0 for Model Exchange and for Co-Simulation have been merged and several new features have been added.

**The following changes in FMI 2.0 are** **not backwards compatible due to the merging**:

File fmiModelTypes.h (in FMI for Model Exchange) has been renamed to fmi2TypesPlatform.h (the file name used in FMI for Co-Simulation).

File fmiModelFunctions.h (in FMI for Model Exchange) has been renamed to fmi2Functions.h (the file name used in FMI for Co-Simulation), and the function prototypes in this header files have been merged from “Model Exchange” and from “Co-Simulation”). Additionally, a new header files has been added, fmi2FunctionTypes.h that contains a definition of the function signatures. This header file is also used in fmi2Functions.h (so the signature is not duplicated). The benefit is that fmi2FunctionTypes.h can be directly used when loading a DLL/sharedObject (in FMI 1.0, the tool providers had to provide this header file by themselves).

Fixing ticket #47:  
In FMI 1.0 for Model Exchange the fmiModelDescription.version was defined as string, whereas in Co-Simulation it was defined as integer. This has been changed, so that version is a string.

**The following backwards compatible improvements have been made in FMI 2.0:**

The FMI 1.0 documents have been merged (for example, all common definitions have been placed in the new chapter 2).

**The following not backwards compatible improvements have been made in FMI 2.0:**

Element “fmiModelDescription.Implementation” in the model description schema file has been replaced by a different structure where one hierarchical level is removed. There are now 2 elements directly under fmiModelDescription: “ModelExchange” and “CoSimulation”.  
File “fmiImplementation.xsd” has been removed.  
New capability flags have been introduced both for ModelExchange and for CoSimulation, such as canGetAndSetFMUstate, canSerializeFMUstate, etc.  
 Attribute modelIdentifier has been moved from an fmiModelDescription attribute to an attribute in ModelExchange and in CoSimulation. This allows providing different identifiers, and then an FMU may contain both distribution types with different DLL names (which correspond to the modelIdentifier names).  
 A new attribute needsExecutionTool has been introduced both in ModelExchange and in CoSimulation in order to define whether a tool is needed to execute the FMU. The previous elements in CoSimulation\_Tool have been removed.

The state machines of ModelExchange and CoSimulation have been improved. Especially, the entering of the states in this state machine are now clearly marked by corresponding function calls (fmi2EnterInitializationMode, fmi2EnterEventMode, fmi2EnterContinuousTimeMode).

Fixing ticket #9:  
A new element LogCategory was introduced in fmiModelDescription. This is an unordered set of strings representing the possible values of the log categories of the FMU (for example logEvent).  
Function fmi2SetDebugLogging has two new arguments to define the categories (from LogCategory) to be used in log messages.

Fixing ticket #33:  
The causality and variability attributes of a ScalarVariable have not been fully clear. This has been fixed by changing the enumeration values of variability from “constant, parameter, discrete, continuous" to "constant, fixed, tunable, discrete, continuous" and causality from “input output internal none” to “parameter, input, output, local”. This change includes now also the support of parameters that can be tuned (changed) during simulation.

Fixing ticket #35:  
In order to simplify implementation (for example, an “element event handler” is no longer needed in SAX XML parser), the only location where data is not defined by attributes, is changed to an attribute definition: Element DirectDependency in ScalarVariable is removed. The same information can now be obtained from the InputDependency attribute inside <fmiModelDescription><ModelStructure><Outputs>.

Fixing ticket #37:  
The new status flag fmi2Terminate is added to the Co-Simulation definition. This allows a slave to terminate the simulation run before the stop time is reached without triggering an error.

Fixing ticket #39:  
Wrong example in the previous section 2.10 of Co-Simulation has been fixed.

Fixing ticket #41:  
New types introduced in fmi2TypesPlatform.h :  
 fmi2ComponentEnvironment, fmi2FMUstate, fmi2Byte.  
Struct fmi2CallbackFunctions gets a new last argument:   
 fmi2ComponentEnvironment componentEnvironment  
The first argument of function logger is changed from type fmi2Component to fmi2ComponentEnvironment.  
By these changes, a pointer to a data structure from the simulation environment is passed to the logger and allows the logger, for example, to transform a valueReference in the log message to a variable name.

Fixing ticket #42:  
Enumerations defined in fmi2Type.xsd are now defined with (name, value) pairs. An enumeration value must be unique within the same enumeration (to have a bijective mapping between enumeration names and values, in order that results can optionally be presented with names and not with values).  
Furthermore, the min/max values of element Enumeration in TypeDefinition have been removed because they are meaningless.

Fixing ticket #43:  
The previous header file fmiFunctions.h is split into 2 header files, fmi2FunctionTypes.h and fmi2Functions.h, in order to simplify the dynamic loading of an FMU (the typedefs of the function prototypes defined in fmi2FunctionTypes.h can be used to type case the function pointers of the dynamic loading).

Fixing ticket #45:  
Contrary to the ticket proposal, no new function fmiResetModel is added. Instead 6 new functions are added to get and set the internal FMU state via a pointer and to serialize and deserialize an FMU state via a byte vector provided by the environment. For details, see section 2.1.8. This feature allows, for example, to support more sophisticated co-simulation master algorithms which require the repetition of communication steps. Additionally, two capability flags have been added (canGetAndSetFMUstate, canSerializeFMUstate) in order to define whether these features are supported by the FMU.

Fixing ticket #46:  
The unit definitions have been enhanced by providing an optional mapping to the 7 SI base units and the SI derived unit “rad”, in order for a tool to be able to check whether a signal provided to the FMU or inquired by the FMU has the expected unit.

Fixing ticket #48:  
The definition of fmiBoolean in fmiTypesPlatform.h for “standard32” was changed from char to int. The main reason is to avoid unnecessary casting of Boolean types when exporting an FMU from a Modelica environment or when importing it into a Modelica environment.  
The current definition of char for a Boolean was not meaningful, since, for example, for embedded code generation usually Booleans are packed on integers and char for one Boolean would also not be used. It is planned to add more supported data types to an FMU in the future, which should then also include support for packed Booleans.

Fixing ticket #49:  
Argument fmiComponent in function pointer stepFinished was changed to fmi2ComponentEnvironment (when stepFinished is called from a co-simulation slave and provides fmi2ComponentEnvironment, then this data structure provided by the environment can provide environment specific data to efficiently identify the slave that called the function).

Fixing ticket #54:  
In section 2.3 it is now stated, that the FMU must include all referenced resources. This means especially that for Microsoft VisualStudio the option “MT” has to be used when constructing a DLL in order to include the run-time environment of VisualStudio in the DLL.

Fixing ticket #75:  
Since states are now explicitly defined in the xml-file, function fmiGetStateValueReferences is no longer needed, as well as the special type fmiUndefinedValueReference that might be used as return value of this function. Therefore, both elements have been removed in FMI 2.0.

Fixing ticket #85:  
New argument noSetFMUStatePriorToCurrentPoint to function fmi2CompletedIntegratorStep, similarly to fmi2DoStep, in order that the FMU can flush a result buffer if necessary.

Fixing ticket #86:  
The fmi2TypesPlatform.h header file has been slightly changed: The default value of fmi2TypesPlatform is changed from “standard32” to “default”, since this definition holds for most platforms and compilers. Furthermore, the default type of fmi2ValueReference has been changed from “unsigned int” to “size\_t”.

Fixing ticket #88:  
The definition of fmi2Functions.h slightly changed to improve portability (the header file can now be utilized both for Microsoft and gnu compilers, and the danger of name conflicts has been reduced).

Fixing ticket #95:  
FMI xml-files need to be UTF-8 encoded (as are xml schema files and strings in the C-API), in order to simplify reading of xml-files.

Fixing ticket #113:  
Changed function name “fmiTerminateSlave” to “fmi2Terminate” in order to be consistent with the other function definitions (fmi2EnterSlaveInitializationMode, fmi2Terminate).

Fixing ticket #115:  
Clarification added, that the special values NAN, +INF, -INF, are not allowed in the FMI xml-files.

Fixing ticket #127:  
Added clarifications in section 2.1, that all C-API functions are not thread safe and that FMUs must not influence each other.

Fixing ticket #218:  
Changed all name prefixes from fmi to fmi2 in \*.h, \*.xsd, \*.png files and in the specification to avoid compiler and linker problems when supporting both FMI 1.0 and 2.0 in the same program.

Function fmiInitialize was split into two functions: fmi2EnterInitializationMode and fmi2ExitInitializationMode in order that artificial or “real” algebraic loops over connected FMUs can be handled in an efficient way.

Function stepEvent in struct fmi2CallbackFunctions had different locations in the FMI documentation and in the header file. This inconsistency has been corrected by using the location in the header file (at the end of the struct).

The struct fmi2CallbackFunctions is provided as a pointer to the struct when instantiating an FMU, and not as the struct itself. This simplifies the importing of an FMU into a Modelica environment.

Defined how to utilize the min/max attributes for fmi2SetReal, fmi2SetInteger, fmi2GetReal, fmi2GetInteger calls.

Attributes “numberOfScalarVariables”, “numberOfContinuousStates”, “numberOfInputs”, “numberOfOutputs” available in FMI 1.0 have been removed, because they can be deduced from the remaining xml file (so in FMI 2.0 this would have been redundant information).

* + 1. Contributors

The development group for this version was headed by Torsten Blochwitz (ITI). The essential part of the design of this version was performed by (alphabetical list):

Johan Akesson, Modelon, Sweden

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The FMI 2.0 document was edited by Martin Otter (DLR), Torsten Blochwitz (ITI), and Martin Arnold (Uni Halle). The State Machines and tables for the Calling Sequences for Model Exchange and Co-Simulation are from Jakob Mauss (QTronic).

This version was evaluated with prototypes implemented for (alphabetical list):

Dymola by Peter Nilsson, Karl Wernersson, and Sven Erik Mattson, Dassault Systèmes, Sweden

FMI Compliance Checker by Iakov Nakhimovski, Modelon AB, Sweden

LMS Imagine.Lab AMESim by Antoine Viel, Siemens PLM Software, France

MapleSim, by Kaska Kowalska, Maplesoft, Canada

Silver by Andreas Junghanns, QTronic, Germany

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xMOD by Mongi ben Gaid, Bertrand Hugon, Bruno Léty, and Fabien Debertolis, IFPEN, France

These prototypes have been used to refine the design of “FMI 2.0 for Model Exchange and Co-Simulation”.

The open source FMITest library (<https://github.com/modelica/FMIModelicaTest>) to test difficult cases of connected FMUs was implemented by Martin Otter (DLR, Germany) based on suggestions by Hilding Elmqvist (Dassault Systèmes, Sweden) and Torsten Blochwitz (ITI, Germany).

The following partners participated at FMI 2.0 design meetings and contributed to the discussion (alphabetical list):

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The following people contributed with comments (alphabetical list):

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Andreas Pfeiffer, DLR RMC-SR

* + 1. FMI 2.0.1 maintenane release: changes and contributors

The changes w.r.t. FMI 2.0 (clarifications and bugfixes) are summarized on the release page for FMI 2.0.1  
<https://github.com/modelica/fmi-standard/releases/tag/v2.0.1>

The following partners participated at FMI 2.0.1 meetings (alphabetical list):

Christian Bertsch, Robert Bosch GmbH, Germany  
Torsten Blochwitz, ESI ITI GmbH, Germany  
Robert Braun, Linköping University, Sweden  
Andreas Junghanns, QTronic GmbH, Germany  
Pierre R. Mai, PMSF IT Consulting, Germany  
Masoud Najafi, Altair, France  
Andreas Pillekeit, dSPACE GmbH, Germany  
Torsten Sommer, Dassault Systèmes, Germany  
Karl Wernersson, Dassault Systèmes, Sweden

For further contributors by comments please refer to the issue tracking system <https://github.com/modelica/fmi-standard/milestone/3>

* + 1. FMI 2.0.2 maintenane release: changes and contributors

The changes w.r.t. FMI 2.0.1 (clarifications and bugfixes) are summarized on the release page for FMI 2.0.2  
https://github.com/modelica/fmi-standard/releases/tag/v2.0.2

For contributors please refer to the issue tracking system [https://github.com/modelica/fmi-standard/milestone/](https://github.com/modelica/fmi-standard/milestone/3)15

* + 1. FMI 2.0.3 maintenane release: changes and contributors

The changes w.r.t. FMI 2.0.2 (clarifications and bugfixes) are summarized on the release page for FMI 2.0.3 https://github.com/modelica/fmi-standard/releases/tag/v2.0.3

For contributors please refer to the issue tracking system <https://github.com/modelica/fmi-standard/milestone/18>

* + 1. FMI 2.0.4 maintenance release: changes and contributors

The changes w.r.t. FMI 2.0.2(clarifications and bugfixes) are summarized on the release page for FMI 2.0.3 https://github.com/modelica/fmi-standard/releases/tag/v2.0.4

For contributors, please refer to the issue tracking system <https://github.com/modelica/fmi-standard/milestone/22>

For the backported “Terminals and Icons” and “Build Configuration” features refere to the contributors list to FMI3.0 <https://fmi-standard.org/docs/3.0/#_contributors>

1. Glossary

This glossary is a subset of (*MODELISAR Glossary, 2009*) with some extensions.

| **Term** | **Description** |
| --- | --- |
| *algorithm* | A formal recipe for solving a specific type of problem. |
| *application programming interface (API)* | A set of functions, procedures, methods or classes together with type conventions/declarations (for example, C header files) that an operating system, library or service provides to support requests made by computer programs. |
| *AUTOSAR* | AUTomotive Open System ARchitecture ([www.autosar.org](http://www.autosar.org/)). Evolving standard of the automotive industry to define the implementation of embedded systems in vehicles including communication mechanisms. An important part is the standardization of C functions and macros to communicate between software components. AUTOSAR is targeted to build on top of the real-time operating system OSEK ([www.osek-vdx.org](http://www.osek-vdx.org/), [de.wikipedia.org/wiki/OSEK](http://de.wikipedia.org/wiki/OSEK)). The use of the AUTOSAR standard requires AUTOSAR membership. |
| *communication points* | Time grid for data exchange between master and slaves in a co-simulation environment (also known as “sampling points” or “synchronization points”). |
| *communication step size* | Distance between two subsequent *communication points* (also known as “sampling rate” or “macro step size”). |
| *co-simulation* | Coupling (in other words, dynamic mutual exchange and utilization of intermediate results) of several *simulation programs* including their numerical solvers in order to simulate a system consisting of several subsystems. |
| *co-simulation platform* | Software used for coupling several *simulation programs* for *co-simulation.* |
| *ECU* | Electronic Control Unit (Microprocessor that is used to control a subsystem in a vehicle). |
| *event* | Something that occurs instantaneously at a specific time or when a specific condition occurs. At an event, numerical integration is suspended and variables may change their values discontinuously. |
| *FMI* | Functional Mock-up Interface: Interface of a functional mock-up in form of a model. In analogy to the term digital mock-up (see *mock-up*), functional mock-up describes a computer-based representation of the functional behavior of a system for all kinds of analyses. |
| *FMI for Co-Simulation* | Functional Mock-up Interface for Co-Simulation: One of the MODELISAR *functional mock-up interfaces.*  It connects the *master solver* component with one or more *slave solvers*. |
| *FMI for Model Exchange* | Functional Mock-up Interface for Model Exchange: One of the MODELISAR *functional mock-up interfaces.* It consists of the *model description interface* and the *model execution interface*. It connects the *external model* component with the *solver* component. |
| *FMU* | Functional Mock-up Unit: A “model class” from which one or more “model instances” can be instantiated for simulation. An FMU is stored in one ZIP file as defined in section 2.3 consisting basically of one XML file that defines the model variables and a set of C functions (see section 2.1), in source or binary form, to execute the model equations or the simulator slave. In case of tool execution, additionally, the original simulator is required to perform the co-simulation (compare section 4.3.1). |
| *integration algorithm* | The numerical algorithm to solve differential equations. |
| *integrator* | A *software component*, which implements an *integration algorithm*. |
| *interface* | An abstraction of a *software component* that describes its behavior without dealing with the internal implementation. *Software components* communicate with each other via interfaces. |
| *master/slave* | A method of communication, where one device or process has unidirectional control over one or more other devices. Once a master/slave relationship between devices or processes is established, the direction of control is always from the master to the slaves. In some systems, a master is elected from a group of eligible devices, with the other devices acting in the role of slaves. |
| *mock-up* | A full-sized structural, but not necessarily functional model built accurately to scale, used chiefly for study, testing, or display. In the context of computer aided design (CAD), a digital mock-up (DMU) means a computer-based representation of the product geometry with its parts, usually in 3-D, for all kinds of geometrical and mechanical analyses. |
| *model* | A model is a mathematical or logical representation of a system of entities, phenomena, or processes. Basically, a model is a simplified abstract view of the complex reality.  It can be used to compute its expected behavior under specified conditions. |
| *model description file* | The model description file is an XML file, which supplies a description of all properties of a *model* (for example input/output variables). |
| *model description interface* | An interface description to write or retrieve information from the *model description file*. |
| *Model Description Schema* | An *XML* schema that defines how all relevant, non-executable, information about a “model class” (*FMU)* is stored in a text file in *XML* format. Most important, data for every variable is defined (variable name, handle, data type, variability, unit, etc.), see section 2.2. |
| *numerical solver* | see *solver* |
| *output points* | Tool internal time grid for saving output data to file (in some tools also known as “*communication points*” – but this term is used in a different way in FMI for Co-Simulation, see above). |
| *output step size* | Distance between two subsequent *output points*. |
| *parameter* | A quantity within a *model*, which remains constant during *simulation (fixed parameter) or may change at event instances (tunable parameter).*Examples are a mass, stiffness, etc. |
| *slave* | see *master/slave* |
| *simulation* | Compute the behavior of one or several *models* under specified conditions.  (see also *co-simulation*) |
| *simulation model* | see *model* |
| *simulation program* | Software to develop and/or solve simulation *models*. The software includes a *solver*, may include a user interface and methods for post processing (see also: *simulation tool*, *simulation environment*).  Examples of simulation programs are: AMESim, Dymola, SIMPACK, SimulationX, SIMULINK. |
| *simulation tool* | see *simulation program* |
| *simulator* | A simulator can include one or more *simulation programs*, which solve a common simulation task. |
| *solver* | *Software component,* which includes algorithms to solve *model*s, for example *integration algorithms* and *event handling* methods. |
| *state* | The “continuous states” of a model are all variables that appear differentiated in the model and are independent from each other.  The “discrete states” of a model are time-discrete variables that have two values in a model: The value of the variable from the previous *event* instant, and the value of the variable at the actual event instant. |
| *state event* | *Event* that is defined by the time instant where the domain z > 0 of an event indicator variable z is changed to z ≤ 0, or vice versa.  This definition is slightly different from the usual standard definition of state events: “*z*(*t*)\**z*(*ti*-1) ≤ 0” which has the severe drawback that the value of the event indicator at the previous event instant, *z*(*ti*-1) ≠ 0, must be non-zero and this condition cannot be guaranteed. The often used term “zero crossing function” for z is misleading (and is therefore not used in this document), since a state event is defined by a change of a domain and not by a zero crossing of a variable. |
| *step event* | *Event* that might occur at a completed integrator step. Since this event type is not defined by a precise time or condition, it is usually not defined by a user. A program may use it, for example, to dynamically switch between different states. A step event is handled much more efficiently than a *state event*, because the event is just triggered after performing a check at a completed integrator step, whereas a search procedure is needed for a state event. |
| *super dense time* | A precise definition of time taking into account iterations at an event. For an *FMU*, the independent variable time is a tuple where . The real part of this tuple is the independent variable of the FMU for describing the continuous-time behavior of the model between events. In this phase . The integer part of this tuple is a counter to enumerate (and therefore distinguish) the events at the same continuous-time instant . |
| *time event* | *Event* that is defined by a predefined time instant. Since the time instant is known in advance, the integrator can select its step size so that the event point is directly reached. Therefore, this event can be handled efficiently. |
| *user interface* | The part of the simulation program that gives the user control over the simulation and allows watching results. |
| *value reference* | The value of a scalar variable of an FMU is identified with an Integer handle called *value reference*. This handle is defined in the modelDescription.xml file (as attribute valueReference in element ScalarVariable). Element valueReference might not be unique for all variables. If two or more variables of the same base data type (such as fmi2Real) have the same valueReference, then they have identical values but other parts of the variable definition might be different (for example min/max attributes). |
| *XML* | eXtensible Markup Language ([www.w3.org/XML](http://www.w3.org/XML/), [en.wikipedia.org/wiki/XML](http://en.wikipedia.org/wiki/Xml)) – An open standard to store information in text files in a structured form. |

1. Modelica is a registered trademark of the Modelica Association, Simulink is a registered trademark of the MathWorks Inc., SIMPACK is a registered trademark of SIMPACK AG. [↑](#footnote-ref-1)
2. For Microsoft and Cygwin compilers, “FMI2\_Export” is defined as “\_\_declspec(dllexport) ” and for Gnu-Compilers “FMI2\_Export” is defined as “\_\_attribute\_\_((visibility("default")))” in order to export the name for dynamic loading. Otherwise it is an empty definition. [↑](#footnote-ref-2)
3. Functions fmi2SetXXX do not usually perform calculations but just store the values that are passed in internal buffers. The actual calculation is performed by fmi2GetXXX functions. Still fmi2SetXXX functions could check whether the input arguments are in their validity range. If not, these functions could return with fmi2Discard. [↑](#footnote-ref-3)
4. Typically, fmi2Error return is for non-numerical reasons, like “disk full”. There might be cases where the environment can fix such errors (eventually with the help of the user), and then simulation can continue at the last consistent state defined with fmi2SetFMUstate. [↑](#footnote-ref-4)
5. The variable that is defined with causality = ″independent″ in the fmiModelDescription.xml file. [↑](#footnote-ref-5)
6. Note that the screenshots of this section have been generated from the schema files with the tool “Altova XMLSpy” ([www.altova.com](http://www.altova.com)). With the enterprise edition of XMLSpy it is possible to automatically generate C++, C# and Java code that reads an XML file of fmiModelDescription.xsd. An efficient open source XML parser is SAX (<http://sax.sourceforge.net/>, <http://en.wikipedia.org/wiki/Simple_API_for_XML>). All data from the XML file is only defined via “attributes” and not via “elements”. Therefore, only an “attribute” handler needs to be defined for a SAX parser. [↑](#footnote-ref-6)
7. Note that elements <ModelVariables> and <ModelStructure> are mandatory, whereas <UnitDefinitions>, <TypeDefinitions>, <LogCategories>, <DefaultExperiment>, <VendorAnnotation> are optional. If an optional element is present, and defines a list (such as <UnitDefinitions>), the list must have at least one element (such as <Unit>). [↑](#footnote-ref-7)
8. If no units are defined, element <UnitDefinitions> must not be present. If 1 or more units are defined, this element must be present. [↑](#footnote-ref-8)
9. This definition is identical to the syntax of an identifier in Modelica version 3.2. [↑](#footnote-ref-9)
10. The notation (*Benveniste et.al. 2010*) is adapted from non-standard analysis to super-dense time, in order to precisely define the value from the previous event iteration. [↑](#footnote-ref-10)
11. This definition is slightly different from the standard definition of state events: “*zj*(*t*)·*zj*(*ti*-1) ≤ 0”. This often-used definition has the severe drawback that *zj*(*ti*-1) ≠ 0 is required in order to be well-defined and this condition cannot be guaranteed. [↑](#footnote-ref-11)