The Functional Mock-up Interface 3.0

- New Features Enabling New Applications

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FMI: Simpler „Plumbing“ for Simulation

- FMI for Model Exchange:
  How to connect systems of equations (ODEs)
- FMI for Co-Simulation:
  How to connect “any” model or tool

- Decouple Know-How between producers and users of FMUs
- Massive Re-use of modelling investment
- Many new use-cases are now viable
- 150+ tools now support FMI:
  See: fmi-standard.org/tools

https://fmi-standard.org/
Motivation for FMI 3.0

150+ tools support FMI now: many users now, many new use-case requests:

- Virtual Electronic Control Units (vECUs):
  - FMI 2.0 works well for physics simulations: better support for vECUs is needed
- Advanced Co-Simulation
  - Co-Simulation is the more popular interface type: improved co-simulation methods are needed to improve performance and accuracy
- Multi-FMU simulations are getting more common
  - Events must be synchronized across FMUs
- New ML and AI applications
  - More derivatives computations is required
FMI 3.0: Main Improvements

- Event Mode for Co-Simulation
- Intermediate Variable Update
- Clocks
- New Types
- Array Variables
- Terminals and Icons
- FMI for Scheduled Execution
- Preparation for Layered Standards
FMI 3.0: New Interface Type – Scheduled Execution

Scheduled Execution allows coupling several FMUs with one, external scheduler (OS)
## FMI 3.0: New Data Types

<table>
<thead>
<tr>
<th>FMI 1.0, FMI 2.0</th>
<th>FMI 3.0</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>fmiReal</td>
<td>fmi3Float32</td>
<td>Discrete and continuous variables</td>
</tr>
<tr>
<td></td>
<td>fmi3Float64</td>
<td>States, derivatives, event-indicators</td>
</tr>
<tr>
<td>fmiInteger</td>
<td>fmi3Int8, fmi3UInt8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fmi3Int16, fmi3UInt16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fmi3Int32, fmi3UInt32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fmi3Int64, fmi3UInt64</td>
<td></td>
</tr>
<tr>
<td>fmiBoolean</td>
<td>fmi3Boolean</td>
<td>char</td>
</tr>
<tr>
<td>fmiString</td>
<td>fmi3String</td>
<td>const char* (&quot;\0&quot; terminated, UTF-8 encoded)</td>
</tr>
<tr>
<td></td>
<td>fmi3Binary</td>
<td>const char* (e.g. sensor outputs, bitmaps, …)</td>
</tr>
<tr>
<td></td>
<td>fmi3Clock</td>
<td>Transport information about events</td>
</tr>
</tbody>
</table>
Array Variables (Vectors, Matrices, …)

FMI 1.0 and FMI 2.0:
- Naming convention for array elements (building.room.temp[0], building.room.temp[1], …)
- Array elements are treated as scalars, one valueReference for each variable

FMI 3.0:
- Variables can have multiple <Dimension> elements
- Each dimension can be:
  - Constant: specified by <start> attribute
  - Changeable: depends on a structural parameter which can change its value only in Configuration or Reconfiguration Mode
- fmi3SetXXX, fmi3GetXXX work on whole arrays
Terminals

- Terminals group input and output variables to Terminals, which represent buses or physical connectors
- Predefined matching rules (plug, bus, sequence) for the whole Terminal, other rules are possible

- FMI Terminals are not acausal! The causality (input, output) is defined by the referenced variable!
FMI for Co-Simulation: Event Handling

- **Introduction of Event Mode** like in Model Exchange
- **Event Mode** can be entered by the importer:
  - to handle input events triggered outside the FMU
  - on request of the FMU
- fmi3DoStep(...) can return before communicationStepSize is reached if an FMU internal event needs to be treated outside
- Capability flag hasEventManager signals if event handling is supported by the FMU
- Argument eventModeUsed of fmi3InstantiateCoSimulation signals if event handling is supported by the importer
FMI for Co-Simulation: Intermediate Variable Access

- **FMI1/2 CS**: FMUs exchange values only at communication points.
- **FMI3.0**: allows information exchange between the FMU and the master also at intermediate time points
- Realized with an extension to the state machine: Intermediate update mode which can be entered by the FMU via the callback function `fmi3CallbackIntermediateUpdate(...)` at arbitrary times out of `fmi3DoStep(...)`

- This enables various use cases:
  - Advanced co-simulation algorithms using interpolation / extrapolation techniques
  - Transmission Line Modeling (TLM) co-simulation
  - Input approximation similar to what is possible in FMI 2.0
  - More detailed plotting of simulation results (using additional time point)
Clocks

- Clocks synchronize FMUs with the importer and with other FMUs:
  - Clocks carry the information that a specific event happens
  - Clocked variables belong to one clock (a so-called clocked model partition). They change only if this clock is active.
- Clocks allow precise handling of time events (independent from continuous time: `fmi3SetTime()`, or arguments of `fmi3DoStep()`)

- In **Scheduled Execution** Communication Clocks are used:
  - by the importer to identify the specific partition which is to be executed
  - by the FMU to announce, which model partition wants to be scheduled
## Clock Types

<table>
<thead>
<tr>
<th>Clock Type</th>
<th>causality</th>
<th>interval</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time-based</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>periodic clock</td>
<td>input</td>
<td>constant</td>
<td>Clocked PI-controller with a defined constant interval</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fixed</td>
<td>Clocked PI-controller, interval is defined by periodic \texttt{fmi3SetClock} calls</td>
</tr>
<tr>
<td></td>
<td></td>
<td>calculated</td>
<td>Clocked PI-controller, interval is defined by fixed parameter(s) of the FMU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tunable</td>
<td>Clocked PI-controller, interval is defined by tuneable parameter(s) of the FMU</td>
</tr>
<tr>
<td>aperiodic clock</td>
<td>input</td>
<td>changing</td>
<td>Simulation of the behaviour of a control algorithm with non constant execution time, Generation of pulse sequences</td>
</tr>
<tr>
<td></td>
<td></td>
<td>countdown</td>
<td>Time delayed action after an event, for example ignition signal some time after crankshaft angle event</td>
</tr>
<tr>
<td><strong>Triggered</strong></td>
<td>input</td>
<td>triggered</td>
<td>Control algorithm, triggered by a crankshaft angle sensor</td>
</tr>
<tr>
<td></td>
<td>output</td>
<td>triggered</td>
<td>Crankshaft angle sensor which ticks several times per revolution</td>
</tr>
</tbody>
</table>
Adjoints Derivatives

- In several applications, including backpropagation for gradient-based training AI models, adjoint derivatives ("vector gradient products" (VJPs)) are needed
- They can be implemented efficiently using reverse mode automatic differentiation (AD)
- FMI 3.0 provides now two access functions for partial derivatives:
  - `fmi3GetDirectionalDerivative` to compute the directional derivatives $v_{\text{sensitivity}} = J \cdot v_{\text{seed}}$, and
  - `fmi3GetAdjointDerivative` to calculate the adjoint derivatives $v_{\text{sensitivity}}^T = v_{\text{seed}}^T \cdot J$

Benefit:
- This will allow to more efficiently encapsulate and train AI models with FMI
- Connection of the Python/Julia tool world of AI to the system simulation world
- Enabling the combination of physics-based and AI-based models (e.g. neural ODEs) and training in a unified framework
Concept of Layered Standard

- The layered standard concept allows the specification of standards on top of FMI
- XML element annotations and strings allow additional semantic for variables and terminals
- Extra folder in FMU zip-file allows shipping of additional files at a well-defined place without disturbing compatibility

Examples:
- XCP: When packaging virtual electronic control units (vECUs), XCP allows standardized access (see ASAM) to ECU internal variables (in preparation on FMI GitHub)
- Network2Signals: Allows grouping and description of FMU inputs and outputs as network signals (in preparation on FMI GitHub)
- Including of 3D-Visualization to FMUs which represent multi body simulation models (prototype from ESI ITI and TU Dresden)
### Miscellaneous

- Graphical representations for the whole FMU and for Terminals can be defined.
- Alias variable names are now specified by a list of alias names for each variable and no longer by a separate variable with the same `valueReference`.
- Dependencies might change at runtime due to variable structure of the model or due to changes of array sizes. Dependencies for (array) variables can now be retrieved at runtime.
- Asynchronous execution of `fmi2DoStep` was removed for simplification. This feature was never used and can be implemented by the importer.
- Improvement and clarification of source code FMUs for better platform independency.
Roadmap

- FMI 3.0 Beta 2 is available now
- 2 PlugFests held, 2 more planned in 2021
- We are planning to release FMI 3.0 early 2022
- Resources:
  - Development process can be tracked on GitHub: https://github.com/modelica/fmi-standard
  - FMPy is permanently updated to support FMI 3.0: https://github.com/CATIA-Systems/FMPy
  - Reference FMUs: https://github.com/modelica/Reference-FMUs