TASKING MODELING LANGUAGE: A TOOLSET FOR MODEL-BASED ENGINEERING OF DATA-DRIVEN SOFTWARE SYSTEMS

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ABSTRACT

The interdisciplinary process of space systems engineering poses challenges on the development of its on-board software. The software integrates components from different domains and organizations and has to fulfill requirements, such as robustness, reliability and real-time capability. Model-based methods do not only help to give a comprehensive overview, but they also improve productivity by allowing artifacts to be generated from the model automatically. However, general-purpose modeling languages, such as the Systems Modeling Language (SysML), are not always adequate because of their ambiguity through their generic nature. Furthermore, sensor data handling, analysis, and processing of data in on-board software requires focus on the system's data flow and event mechanism. To achieve this, we developed the Tasking Modeling Language (TML) which allows system engineers to model complex event-driven software systems in a simplified way and to generate software from it. Type and consistency checks on this formal level help to reduce errors early on in the engineering process. While TML is focused on data-driven systems, its models are designed to be extended and customized to specific mission requirements. This paper describes the architecture of TML in detail, explains the base technology, the methodology, and the developed Domain Specific Languages (DSLs). It evaluates the design approach of the software via case study and presents the advantages as well as the faced challenges.

1. INTRODUCTION

Space missions experience a transformation from static pre-flight designed operations towards dynamic in-flight planning. Such a dynamic planning has access to less processing power than (super) computers on ground, but it enables more flexibility because plans can be adjusted while flying. Systems can react on unexpected situations and handle cases where data was not yet available before launch. However, this kind of planning poses new requirements to on-board data processing. Huge amounts of sensor data have to be processed in real-time and, e.g., image processing requires high computational power and time.

Some on-board software such as Attitude and Orbit Control System (AOCS) and the majority of on-board data processing applications can be implemented as a network of data-driven computational nodes. A computational node starts execution when the input data are available and do not need to explicitly wait for the predecessor computational nodes to finish. Also, computational nodes exchange data via data containers which represent interfaces between them. The computational nodes are known as tasks and data containers are referred to as channels, hence, the model is known as task-channel model. This model has potential for modularity, enabling reusability of developed applications. Tasking Framework [1] is an open-source [1] C++ library to develop an on-board software. It consists of abstract classes with virtual methods following the event-driven programming paradigm. In Tasking Framework, an application is realized by a directed graph of connected tasks and channels.

Furthermore, developing the end-to-end data processing pipelines in one system is challenging as components from different institutions have to be integrated and connected. Design changes have to be integrated into source code, documentation and also into the build configuration. Modeling can help this process by generating communication and interface code from central data models [2]. This kind of model-driven software development (MDSD) allows to maintain a central point of truth while also allowing for the re-generation of artifacts to accommodate changes. The model can also be used to validate and simulate the developed design and to communicate

[1] https://github.com/DLR-SC/tasking-framework

changes. However, in data-/event-driven systems, general purpose modeling languages are not suited for MDSD activities [2]. To properly configure when components are executed, the model language needs to incorporate domain-specific aspects.

In this paper, we present such a modeling language for data-driven software systems, based on the open source tool Virtual Satellite.[2] Virtual Satellite targets to model systems in their whole life-cycle [3]. A combination of system design modeling in early-phases followed by the MDSD methodology allows reusing system artifacts in the software model, further improving the productivity and the maintainability.

This paper is structured as follows: the next section introduces relevant literature, Section 3 presents our concept and implementation and Section 4 evaluates our modeling approach by applying it to a space example project.

2. BACKGROUND AND RELATED WORK

In this section we will introduce background in on-board data processing and model-based engineering. Furthermore, we will discuss related work in the domain of model-driven development.

2.1. On-board Data Processing

Aerospace projects have started to include more autonomous systems or subsystems to carry out missions, e.g., on distant celestial bodies. Such systems require more on-board data processing, which demands high performance computing resources. Multi-core platforms are promising to fulfill the computational requirements properly [4] as they provide high performance with low power consumption compared with high frequency uni-processors. However, it is quite often not easy to write applications that execute in parallel, which adds more complexity to the design and implementation processes of on-board data processing applications.

An on-board data processing application can be modeled as a directed data-flow graph, where vertices represent processing nodes and data are forwarded to the next node as in a pipeline. The processing nodes do not explicitly wait for the preceding nodes to finish but are executed as soon as their input data (operands) are available. Therefore, these applications have a high potential for modularity and parallelism. On the one hand, investigating the parallelism mitigates the migration to multi-core platforms. On the other hand, exploiting the modularity can improve the re-usability of developed applications.

In some aerospace missions, on-board data-processing participate in critical operations such as autonomous landing, therefore, they influence the reliability and safety of the mission. In addition to that, on-board data processing applications should be real-time capable because some applications may have end-to-end real-time constraints to guarantee the availability of needed data on time, for example, in autonomous landing [5], on-board rendezvous navigation [6], etc. For these applications, we need to perform a software timing analysis in the course of the verification and validation processes. The analysis should cope with the aforementioned software complexity [7]. Hence, involving more on-board data processing in current and future spaces missions emerges more challenges in the development process of these applications.

2.2. Model-Driven Engineering

The European Space Agency (ESA) develops a tool chain for the MDSD called The ASSERT Set of Tools for Engineering (TASTE) [8]. It focuses on the error prone process of integration of components. TASTE uses a textual language (ASN.1) to define data types and a graphical one (AADL) to model the system architecture. Furthermore, the TASTE generator not only generates source code, but also files for the build configuration of the system.

ESA, furthermore, develops a reference architecture for space systems [9]. It contains a modeling language for specifying, among other things, the components of the system, named "Space Component Model" [10]. The reference architecture does not impose any specific tool, but provides a prototype implementation based on the Eclipse Modeling Framework (EMF)[3]. The reference architecture's modeling environment is based on several Domain Specific Languages (DSLs) and provides code generation capabilities [10].

The Jet Propulsion Laboratory investigated methodologies to reduce the learning overhead of SysML and at the same time add domain-specific notation to the model [11]. They suggest building DSLs based on SysML. However, the generic nature of UML and SysML is challenging for model-driven development with code generation [2]. The large extent of the languages increases learning effort for users. Gray and Rumpe [12] also observed difficulties in using UML and SysML with domain experts that are not familiar with modeling in their day to day life. They suggest investigating whether it is more adequate to design a DSL from scratch rather than customizing an existing general purpose language.

[2] https://github.com/virtualsatellite/

[3] https://www.eclipse.org/modeling/emf/

A case study by Visser [13] investigates domain-specific engineering. He collects guidelines and patterns on how DSLs can be implemented. Before developing a DSL, he suggests doing a domain analysis and investigating which aspects have to be modeled. Atkinson and Kühne [14] describe different forms of meta-modeling for the model-driven development (MDD). They also define a set of technical requirements that MDD techniques should support. They argue that besides available concepts for modeling, the MDD infrastructure has to define notations to depict models, how the model entities represent the real-world elements, concepts to facilitate user extensions, among others.

3. TASKING MODELING LANGUAGE

As highlighted in Section 2.1, developing software for on-board data processing poses new challenges. This section analyses requirements for a model-based solution to these challenges. It, furthermore, presents the design of our modeling environment.

3.1. Domain Analysis

As shown in Figure 1, on-board data processing is highly data-driven. Sensors produce data, processing components analyze it, and finally, actuators react based on these input data. Development of such systems faces some challenges: firstly, the system components (sensors, processing components, actuators) are usually developed by different institutions or obtained from external suppliers. Thus, software for these components might follow different patterns, guidelines, or coding styles but they have to be integrated into one on-board software. Secondly, components themselves and their interactions are subject to frequent changes during the course of the development. Component interfaces might change, processing pipelines could be updated to contain additional or fewer components. All of these changes need to be reflected in multiple places, for instance, in the interface documentation, in the software architecture and subsequent components, etc. As presented in Section 2.2, modeling can counter these challenges by generating artifacts, such as documentation and source code, from a central model. This model, then, reflects a central point of truth. Changes within the system design result in automatically updated (generated) documentation and the source code. Furthermore, affected components get notified/warned about these modifications. However, to benefit from modeling through improved productivity and communication within data-driven projects, models have to focus on certain aspects. We elaborate on these aspects in the following paragraphs.

System components are the software snippets that

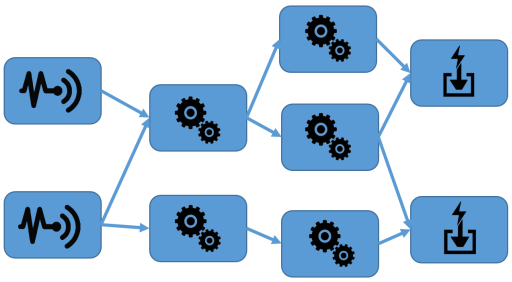

Figure 1. Software for on-board data processing usually contains software components for sensors, processing components and for actuators.

are executed to create, analyze or handle data. However, these components are usually provided by different institutions or are even bought from external suppliers (e.g. device drivers). Integration of these components requires clearly defined interfaces. Furthermore, the software should be modular to enable adding or removing components during the development process.

Data flow is the central aspect of the on-board data processing software. It describes how components are connected with each other and how the communication is structured. Connected components need to have compatible interfaces and the data specifications can be used to check limitations on bandwidth and capacity.

Data input events should be configurable to trigger components once all necessary input data are available. This way, the processing pipeline of an on-board data processing software handles data as fast as possible.

Extensibility is necessary to handle project specific requirements. Projects usually have some additional needs for aspects to be added to the model or some customized artifact generation.

As a result, we pose the following requirements to the modeling environment for on-board data processing:

R.1 The environment shall enable specifying component interfaces in a central point of truth.

R.2 The modeling language shall enable modeling the data flow.

R.3 Execution event handling shall be supported.

R.4 The environment shall be extensible to specific project requirements.

3.2. Concept

A model is an abstraction of a complex system with respect to the relevant aspects for its purpose. To

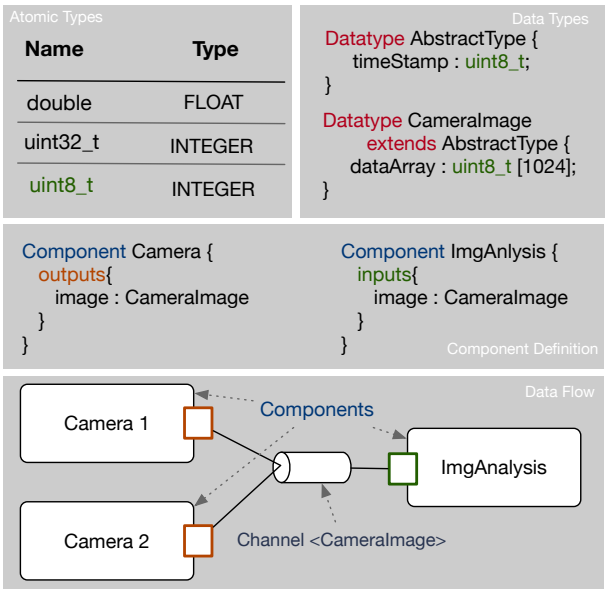

Figure 2. Different types of model representation: Atomic types are specified in a list, data types and components in a textual DSL and the data flow in a graphical diagram.

reduce the learning overhead of the modeling language and to avoid ambiguity, the modeling language should be focused to the model's purpose as much as possible. To model the data flow and event mechanism of the data processing software, we decided to develop a DSL. In contrast to general purpose languages, such as UML or SysML, a DSL only contains aspects that are relevant to our modeling purpose: to boost efficiency in the development of data-driven systems and to improve the communication between different developers.

Model notation. Developing a DSL allows to specify a concrete syntax for the different relevant aspects covered by the model. Modeling component interfaces and a system data flow require to specify applicable data types first. As shown in Figure 2, the simplest way to define data types is to specify available atomic types in a list and then combine these in a textual language. Similar to programming languages, a textual DSL can have keywords to specify properties, such as multiplicity and inheritance. In combination with auto-completion editors, textual DSLs are relatively straightforward to use and creation of elements is fast, as no layout is required (compared to e.g. diagrams). Following this approach, specification of component interface is done in a textual language by using data types to specify inputs, outputs, and parameters.

The data flow connects the different software components and, thereby, provides some system overview. As shown in Figure 2, to facilitate and support this overview, the data flow is modeled in a graphical diagram. Components are represented as nodes, its inputs and outputs are shown as ports on these nodes. It is, then, possible to connect these components via edges. To model n:m connections and to specify the storage / data interface of these connections, users can add channels to the diagram.

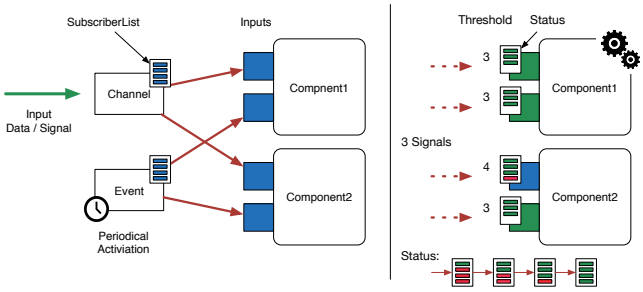

Figure 3. Components are executed event-based. Component inputs subscribe to update events of data channels or other event sources. Once the defined threshold of signals (e.g. number of data items) is reached, the input gets activated. When all inputs are active, the component gets executed.

The different sub-languages for specifying data types, component interfaces, and the data flow represent views on a shared data model. Editors for the different model views integrate changes into the common model. This way, the views and editors are synchronized. For example, if a component is specified to have two inputs and one output, its instances in the diagram will automatically have corresponding ports.

Event handling. As argued in Section 3.1, handling of data events is essential. Components need to be executed once the required input data are available. The event configuration and generated code is based on the Tasking Framework. As shown in Figure 3, components subscribe to their connected input channels to receive notifications about the data availability. Once the threshold of an input data is reached, the corresponding input port is activated. When all input ports are activated, the component gets executed. Input data can also be marked as optional or final. Final inputs automatically execute the component if activated, regardless of the availability of other inputs. Besides data events, it is also possible to trigger components with bare signal events (without data) and periodic timers.

Model checking. System models enable to find problematic aspects and design flaws early on in the engineering process. Tasking Modeling Language (TML) validates that communication channels have compatible types, parameters are filled with correct value types and units are set correctly. Furthermore, users will be notified if components are not

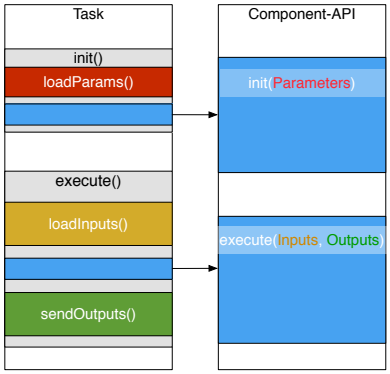

Figure 4. Generated functionality is added into abstract classes, manual customization is implemented in derived classes. If the model is changed, abstract classes are regenerated; the derived classes are not.

connected properly.

Artifact generation. Generators create source code, documentation and configuration files from the model. They are using templates with gaps that are filled with data from the models to create arbitrary documents. To improve the integration process of software components, the generator creates interface classes and communication code. This way, if new elements have to be integrated into the processing pipeline, re-generated source code automatically re-routes the data.

Implementing multi threaded source code for on-board real-time applications can be challenging, even when using frameworks, such as the Tasking Framework. To simplify this kind of software development, goal of the TML and its generator is also to provide a simplified front-end. Users should be enabled to create data- and event-driven on-board software without being expert in multi threaded software. To achieve this, the TML abstracts from the complexity of the generated code. Users only see details that are required to configure the event mechanism of the system. As shown in Figure 4, the code generator prepares incoming data and parameters, and provides a simplified API to components. To enable customization of the generated source code, the generator uses the generation gap pattern.

Extensibility. It is essential to be able to customize the modeling environment to specific project needs. Extensibility of the TML is implemented via multiple levels. First, the model itself can be extended with new elements. Therefore, we use the meta-modeling pattern of *Promotion* [15]. Channel and component types, dynamically defined in the model, can be instantiated in the component diagram. The second level is to customize the code generator by adapting the code templates to specific

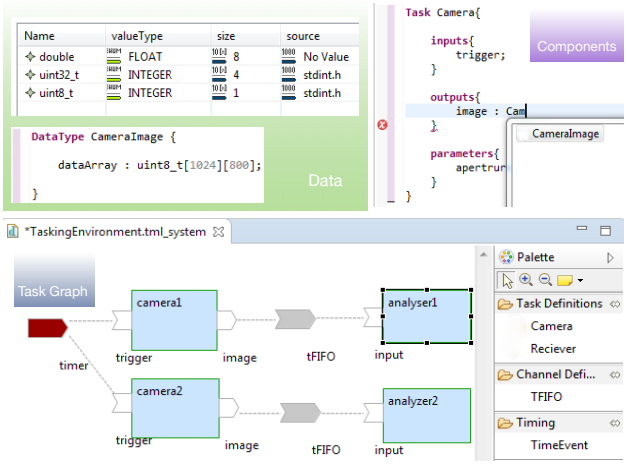

Figure 5. Software for on-board data processing usually contains software components for sensors, processing components and for actuators.

project-needs. And, as mentioned in the last paragraph, the generation gap pattern enables to customize the generated code.

3.3. Implementation

TML is built as an extension of Virtual Satellite[4]. Virtual Satellite is an extensible Model-Based Systems Engineering (MBSE) tool developed and maintained by DLR [3]. Integration of TML in such a systems engineering tool allows reusing already modeled artifacts from early-phase design specifications.

Virtual Satellite is build on top of the Eclipse modeling environment. It assists software engineering by using the MDSD process to generate User Interface (UI) snippets and other software artifacts automatically from the model. The EMF framework provides code generators for producing Java interface and implementation classes for all model entities and their editors. Besides that, the Virtual Satellite layer provides further customization of the model editors, UI snippets, and improves the model validation and verification capabilities. With the help of model validators, Virtual Satellite assists to improve the overall quality of the software product. Furthermore, it also supports backward compatibility of the model by providing model migrators.

Basic attributes of TML model elements, such as e.g. the name, can be modified using generated UI editors. Furthermore, as shown in Figure 5, TML provides customized Xtext[5] editors for specifying datatypes, components, and channel definitions. Keywords, auto-formatting, and syntax highlighting of

[4]https://github.com/virtualsatellite
[5]https://www.eclipse.org/Xtext/

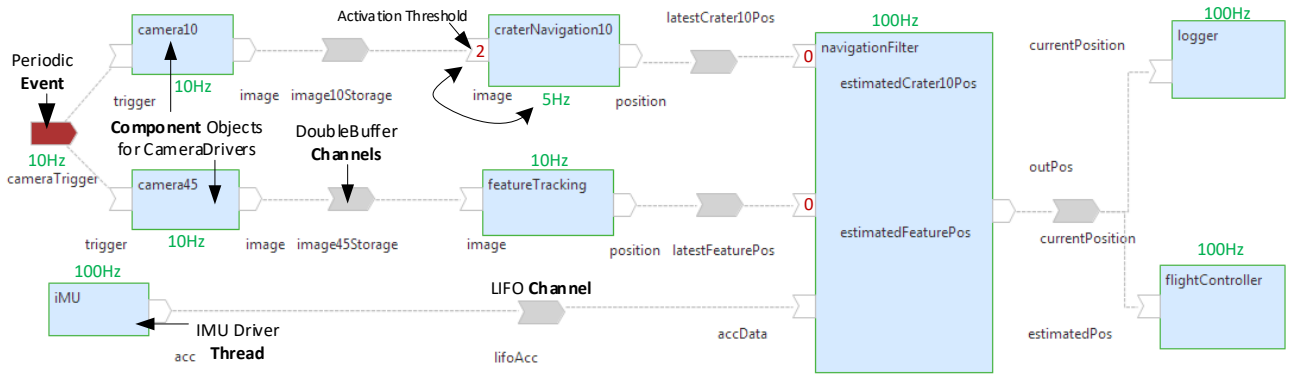

Figure 6. TML component diagram showing the architecture for the optical navigation solution of the project ATON [2]. Cameras are triggered periodically and provide input for some processing components. A navigation filter fuses all processing results and creates an estimated position which is logged and sent to the flight controller.

the DSL editors complement an intuitive user experience. We developed a graphical editor for the data flow using the Graphiti[6] framework in Eclipse. The Graphiti framework provides a simple API to create and synchronize model domain objects with their diagram representations. With one click, users can instantiate tasks, channels, or time-events and connect them together using links. Here, the diagram validates the compatibility of data types when connecting the different components. Furthermore, a double-click on any diagram element opens the respective Virtual Satellite editor where attributes can be modified.

After modeling, the next step within the model-driven development process is the code generation. TML by default provides a code generator integrating the Tasking Framework. Besides the executable C++ source code, the code generator produces unit-test files as well as the build configuration scripts. The code generator follows the generation-gap pattern, which allows the code regeneration preserving the custom modification. This way, TML ensures an incremental software development process while meeting the requirements of an on-board data processing application.

4. CASE STUDY

To evaluate the modeling capabilities of TML, we re-implemented the old SysML model of the project ATON in TML [2]. Figure 6 shows the component diagram of this implementation. The general architecture is data flow oriented and components are executed once their required input data is available. The cameras are triggered by a periodic event (10 Hz) and their image is consumed by two processing components. To reduce the frequency of the crater navigation component, users can specify an activation threshold. The crater navigator shown in Figure 6 is only executed at the rate of 5 Hz as it is only activated with every second available image.

The Inertial Measurement Unit (IMU) is executed as a (non-Tasking Framework) thread with a frequency of 100 Hz. The threshold of "0" on the navigation filter inputs from the two image processing components specifies them as optional. This way, data from these components are used if available but they are not required. As a result, the navigation filter is executed with the same frequency as the IMU, because every data message from IMU triggers an execution.

4.1. Evaluation of the Requirements

The data flow diagram in Figure 6 shows how requirement R.1 and R.2 are fulfilled. The data flow is presented in the graphical diagram, showing all component instances and their connection with each other. Component types are, furthermore, represented in a textual language. The event handling (Requirement R.3) is implemented within the element properties of trigger events and component inputs.

Figure 7 shows how the new channel type `SynchTaskMessageChannel` is added to the model. This new type, with its parameters, is then instantiated in the component diagram (right upper part in Figure 7). The TML generator creates base classes for these type extensions and instantiates them in the object model as specified in the component diagram. Parameter values, as specified in the model, are added to the generated base classes as slot and their value is added in the object instances (bottom of Figure 7). This way, the TML allows using new, extended channel types in the generated communication source code. Thereby, our implementation of MDSD with the TML meets all our requirements to the modeling infrastructure.

[6] https://www.eclipse.org/graphiti/

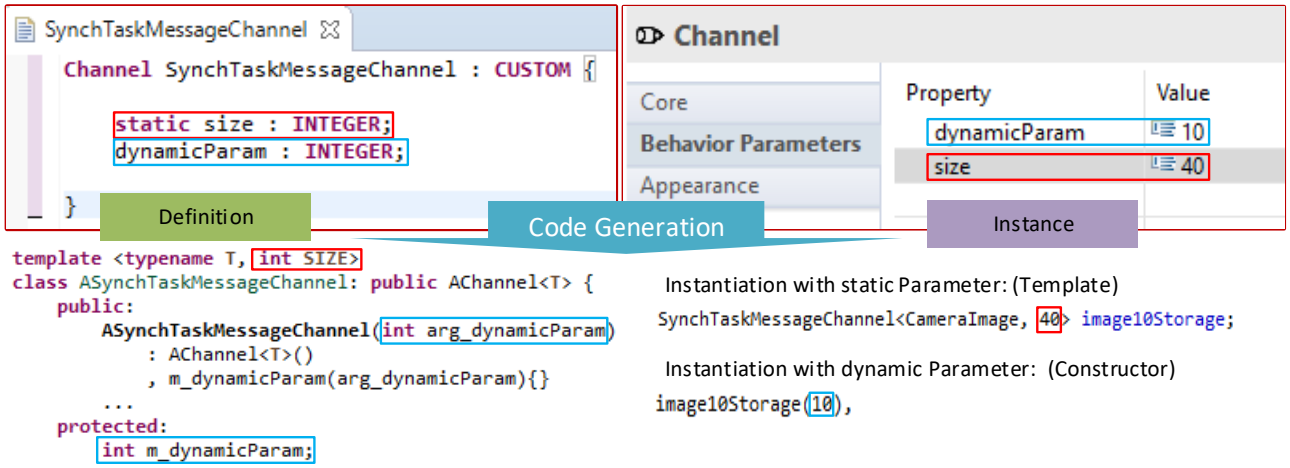

Figure 7. The channel type extension mechanism. Channel types can define parameters that are available in its instances in the model and also in the generated code. The implementation type 'CUSTOM' creates base classes for its implementation and instantiates this class in the system's object model.

4.2. Comparison with the SysML Solution

Model-driven development with the TML was developed as a successor of the implementation based on SysML [2]. While this initial approach increased productivity of the development process, a conclusion of the work was that the modeling language could be improved. The development of the TML represents the advancement of the modeling language by designing the language explicitly for the purpose of data and event driven software systems. A component diagram in UML or a block diagram in SysML, both, allow adding more than 40 different element types to the diagrams. In contrast, a TML component diagram allows only four different element types (triggers, components, channels and connections). Inputs and outputs of the different components are added automatically. This way, TML helps to maintain consistency and reduces ambiguity of the modeling language. As shown in Figure 8, that also has influence on the code generator. Unlike the SysML version, the TML generator does not have to transform the general-purpose modeling elements to the on-board data processing domain. Furthermore, as all model elements have a direct mapping to the source code, their parameters have clear constraints and can be checked.

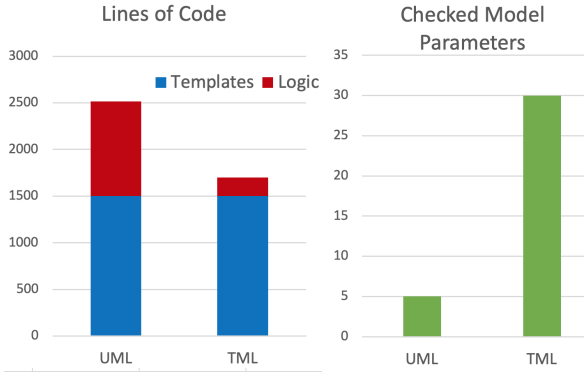

Figure 8. Comparison of the code generator with UML/SysML and TML model. Generation from the TML model needs less mapping and transformation logic. It furthermore contains more domain-specific validation of properties.

5. CONCLUSION AND FUTURE WORK

Sensor data handling, analysis, and processing of data in on-board software requires focus on the system's data flow and event mechanism. To achieve this, we developed TML, a language for event and data-driven software systems. TML incorporates a set of textual and graphical DSLs, which allow system engineers to model complex event-driven software systems in a simpler way and to generate software from it. The textual DSLs in TML provide a strong-typed syntax to define data types and system components, whereas a graphical DSL enables to design the composition and data flow of the system. The TML environment facilitates MDSD by incorporating a code generator which generates executable C++ source-code, unit tests, its build configuration and documentation. This way, the model acts as a single point of truth, and changes on the data flow or integration of new components become trivial. By default, the code generator utilizes the Tasking Framework, an open-source C++ software execution platform developed by DLR. This allows software modules to run concurrently in separate tasks, exchange data between them via channels, and to schedule the task-execution based on events, such as input data availability. TML is focused on data-driven systems, but its infrastructure and models are

designed to be extended and customized to specific mission requirements. It provides three levels of extension mechanism: firstly, new components, channel types, and parameters can be added to the model dynamically. Secondly, the code generator can be customized by extending or implementing new code templates. This enables to support new execution environments or even new programming languages. Lastly, the generated code is designed to be extended by manually written code. This combination of a modeling language, customized to data-flow oriented systems with a highly extensible artifact generation, enables effective support for the development of an on-board software.

Future work will focus on extending formal verification of the TML models. Goal is to search for potential dead- and live-locks, and to analyze and improve the data flow of the system. Projects building up on the TML are investigating reconfiguration planning of an on-board software modeled with the TML [16]. TML will also evolve and improve by facilitating new features of the Tasking Framework.

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