Application Engineering for Embedded Systems
Transforming SysML Specification to Simulink within a Product-Line based Approach

Vanderson H. Fragal, Rogério F. Silva, Itana M. S. Gimenes and Edson A. Oliveira Júnior
Department of Informatics-DIN, Universidade Estadual de Maringá-UEM, Maringá-PR, Brazil

Keywords: Software Product Line, SysML, Simulink, Unmanned Aerial Vehicle, Model Transformation.

Abstract: The evolution of hardware platforms has transferred a great amount of functionality to embedded software, thus increasing its complexity. Model Driven Engineering (MDE) and Software Product Line (SPL) can enhance the development of complex embedded systems by using different specification languages according to the abstraction levels and controlling variability across development. The SyMPLES approach allows the creation of SysML-based SPLs. It includes two SysML extensions, created by means of the UML profiling mechanism both to express SPL variability concepts and to associate SysML blocks to the main classes of functional blocks. This paper presents the transformation process from SysML to Simulink models. SysML models, created in the SPL application engineering activity of SyMPLES, are used to generate functional blocks and state machines in Simulink. An application example was developed for one subsystem of an autopilot board used in Unmanned Aerial Vehicles, named Yapa 2 of Paparazzi project, which was studied into the context of National Institute of Science and Technology for Safety Critical Embedded Systems (INCT-SEC).

1 INTRODUCTION

Embedded systems are applications for processing embedded information in a larger product which is not usually directly visible to users (Marwedel 2010). The increased computational power of hardware platforms has led to a fast growth of embedded software over the last decades mainly due to the transfer of more functionality to software (Burch et al. 2001). As a consequence, embedded systems became larger and more complex, thus more demanding in terms of software engineering techniques. The Software Product Line (SPL) approach (Linden et al., 2007) has been successfully applied to embedded system (Polzer et al., 2009; Fragal et al., 2011; Braga et al., 2011).

The Model Driven Engineering (MDE) approach supports the generation of applications by means of model transformation, which may be at the same or different abstraction levels (Czarnecki and Helsen, 2003). During development, various modeling languages are used to represent the required abstraction levels. For example, UML/SysML languages are used to represent higher abstraction level models (Burch et al., 2001; Brisolara, 2007), while Simulink (Simulink, 1994) is used to represent lower abstraction level models (Polzer et al. 2009; Pastor et al. 2006).

Simulink is a tool used in the development of embedded systems that represents more than 50% of the market (Ebert and Jones, 2009). Functional blocks based on libraries are used to represent behavior and specific functions which are used as input to generate C code with Simulink Coder (or Real-Time Workshop) plug-in (Simulink Coder 2012). There are some approaches that describes SPL based on Simulink (Pastor et al., 2006; Steiner, 2012). However, they need to add control blocks in the Simulink model to specify variability which increases the complexity of product specific models.

Thus, there is a need to represent variability of SPL at a higher abstraction level. The management of variability at higher abstraction level models enables the configuration of products in a top-down development without adding complexity to lower abstraction level models.

Systems Modelling Language (SysML) (SysML 2008) is a language for specification of embedded systems used in the Object-Oriented Systems

Engineering Method (OOSEM) (Lykins 2000). This method supports the SysML specification of embedded systems from initial requirements elicitation, analysis and design through the integration between hardware and software, validation and testing.

SysML-based Product Line Approach for Embedded Systems (SyMPLES) (Silva 2012) is based on OOSEM. It supports the creation of SysML-based artifacts with variability management mechanisms.

This paper presents the process used in the SyMPLES application engineering activity to transform SysML models to Simulink ones. The process has 3 activities: (i) generate the SPL product; (ii) execute an intermediary ATLAS Transformation Language (ATL) (Obeo 2006) transformation; and (iii) create a Matlab script using both Simulink and Stateflow Application Programming Interfaces (API).

An application example of the transformation process was carried out in order to design a part of a flight controller for an autopilot board named Yapa 2 of the Paparazzi project (YAPA 2011).

This paper is organized as follows: Section 2 presents a background summary; Section 3 presents the transformation process approach and its activities; Section 4 presents an application example of the transformation process for the Yapa 2 board. Section 5 presents discussion and related works; and Section 6 presents conclusions and future work.

2 BACKGROUND

Important concepts related to the application of the SyMPLES approach are presented in this section.

SyMPLES consists of two SysML extensions named *SyMPLES Profile for Representation of Variability* (*SyMPLES-ProfileVar*) and *SyMPLES Profile for Functional Blocks* (*SyMPLES-ProfileFB*). SyMPLES also consists of two processes that use these extensions, named *SyMPLES Process for Product Lines* (*SyMPLES-*ProcessPL) and *SyMPLES Process for Identification of Variabilities (SyMPLES-ProcessVar)*.

SyMPLES-ProfileVar is based on the UML profile defined in the SMarty approach (Oliveira et al. 2010). SyMPLES-ProfileFB is based on a set of stereotypes that represents the main classes of functional blocks, which aims at representing the behavior associated with standard SysML blocks. Using Model Driven Engineering (MDE) techniques, SyMPLES-ProfileFB stereotypes can be mapped and used to generate functional blocks. A SysML model, created by a SyMPLES SPL configuration, can be transformed to a Simulink model, including functional blocks and state machines, at a lower abstraction level, which can then generate code.

In addition to the SysML extensions to represent variability, SyMPLES defines two processes that use such extensions for supporting the specification of a SysML-based SPL. SyMPLES-ProcessPL defines a set of activities and guidelines for guiding the user in creating the SPL artifacts from the use cases definition and requirements structuring phase to the analysis and design phases; and SyMPLES-ProcessVar which is concurrently executed with the first process and contains a set of activities and guidelines for supporting the user in the identification, definition and representation of variability, as well as the SPL product configuration.

In this paper, we use the SyMPLES-ProfileFB that is composed of a group of stereotypes for mapping functional blocks and providing additional semantics to SysML blocks. Thus, it is possible to associate a certain type of behavior to a standard SysML block to facilitate the specification of embedded systems (Silva 2012).

The models represented in SysML that use SyMPLES-ProfileFB and SyMPLES-ProfileVar are used as input to the SPL application engineering activity. Artifacts generated in this activity can be transformed to Simulink models. For example, the SyMPLES-ProfileFB stereotype <<constant>> was added to the attribute value. An initial value can be linked to that stereotype and mapped together to a functional block as a parameter. Figure 1 shows an example of a SysML part block in an internal block diagram. This part represents a battery charge sensor mapped to a Simulink functional block.

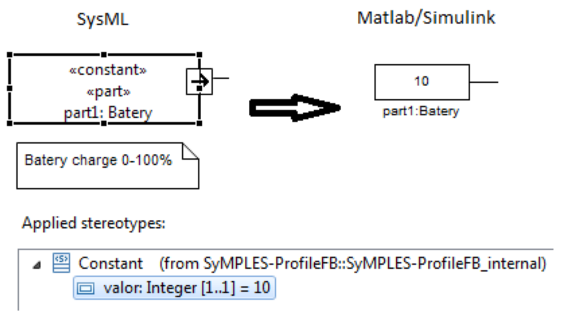


Figure 1: Example of SysML element with a SyMPLES-ProfileFB stereotype.

3 SYMPLES TRANSFORMATION PROCESS

In this section, we present the transformation process of the SyMPLES approach which takes SysML models and convert them to Simulink models. It consists of three activities: generate the configured SysML architecture; execute ATL transformation; and, generate functional blocks.

3.1 Generate Configured SysML Architecture

The configuration of SysML architecture considered three SysML diagrams. These diagrams are: (i) Block Definition diagram; (ii) Internal Block diagram; and (iii) State Machine diagram. Figure 2 shows the relationship between the SysML diagrams used and the application of SyMPLES profiles.

The root diagram is the Block Definition which describes the main blocks of the system. A block can be further represented either as an Internal Block diagram describing its internals relationship based on block instances or as a State Machine diagram which represent its specific behavior.

The transformation process uses the SyMPLES-ProfileFB to map blocks or blocks instances. It only considers Internal Block or State Machine diagrams from blocks that use the <<subsystem>> stereotype.

The Block Definition and Internal Block diagrams can also have SyMPLES-ProfileVar stereotypes applied to its elements. These stereotypes support the configuration of a SPL product in the application engineering activity.

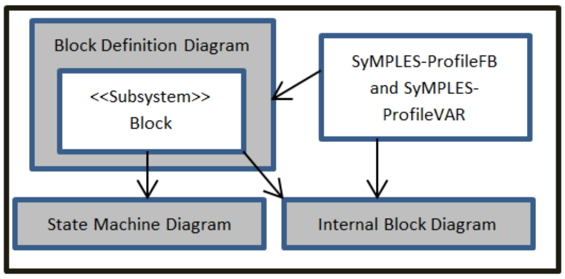


Figure 2: SysML diagrams used and the use of SyMPLES Profiles.

3.2 Execute ATL Transformation

ATL can use models based on the Eclipse Modeling Framework (EMF) (EMF 2012) to perform transformations. The EMF uses the standard Ecore to represent its metamodels. Papyrus (Papyrus, 2012) and TOPCASED (TOPCASED 2012) are examples of tools that have SysML graphical editors based on Ecore metamodels. Graphical editors based on Ecore uses two synchronized XMI files to store the modeled elements: (i) domain file – represents a UML file with attributes (eg. name, types and relationship) and profile stereotypes; and (ii) graphical file – one or more files can be associated with the domain file. Papyrus SysML editors use a Notation (Hunter 2012) file to persist graphical data (eg. diagrams, size and position of elements). These files are used by a Diagram Interchange (DI) (OMG 2006) file.

The ATL transformation gathers relevant information from the SysML model configured and generates a file based on a Simulink metamodel. This intermediate transformation makes the transformation process flexible to deal with other SysML editors based on EMF. Figure 3 shows the elements used in the ATL transformation in layered metamodels. Layered metamodels are introduced in (Ruscio 2007). The SysML configured model and its Notation file are used as input to the transformation, and a XMI Simulink model is generated. The Simulink metamodel was adapted from (Biehl et al. 2010).

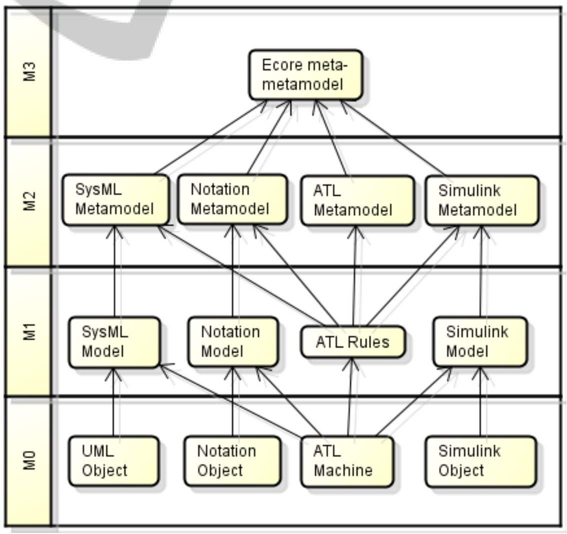
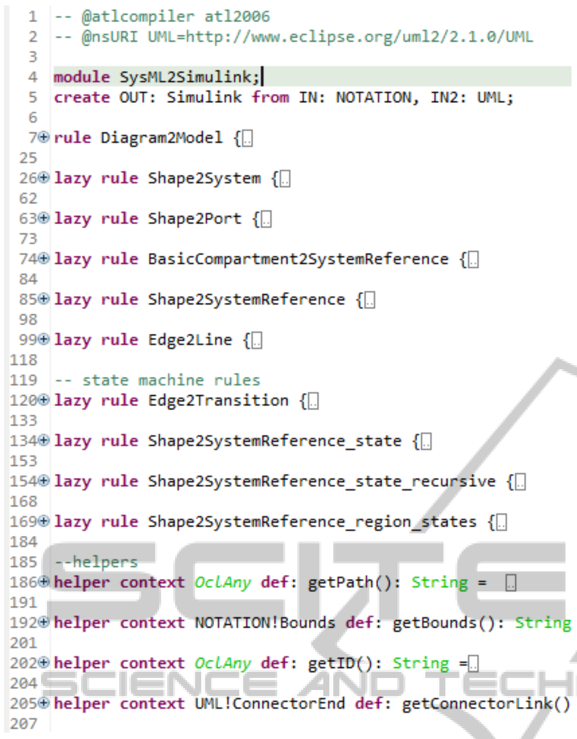


Figure 3: Models used in the ATL transformation in layered metamodels.

To execute the transformation a set of ATL rules are needed. Figure 4 shows the rules created in this work to execute in an ATL machine. The transformation rules include elements of a block definition diagram, internal block diagrams and state machines.



```
-- @atlcompiler atl2006
-- @nsURI UML=http://www.eclipse.org/uml2/2.1.0/UML

module SysML2Simulink;
create OUT: Simulink from IN: NOTATION, IN2: UML;

rule Diagram2Model {□

lazy rule Shape2System {□

lazy rule Shape2Port {□

lazy rule BasicCompartment2SystemReference {□

lazy rule Shape2SystemReference {□

lazy rule Edge2Line {□

-- state machine rules
lazy rule Edge2Transition {□

lazy rule Shape2SystemReference_state {□

lazy rule Shape2SystemReference_state_recursive {□

lazy rule Shape2SystemReference_region_states {□

--helpers
helper context OclAny def: getPath(): String = □

helper context NOTATION!Bounds def: getBounds(): String

helper context OclAny def: getID(): String =□

helper context UML!ConnectorEnd def: getConnectorLink()
```

Figure 4: ATL rules used in the ATL transformation.

3.3 Generate Functional Blocks

The generation of functional blocks creates a script that generates a Simulink model. Figure 5 shows the sequence of artifacts (gray scale) produced. The Notation and UML files are obtained from the SyMPLES SPL artifacts and are used in the ATL transformation. The UML file and the XMI file created in the ATL transformation activity are used to create a Matlab script using Java code. The UML file is necessary as input to Java code because the SyMPLES-ProfileFB stereotypes are necessary to map elements in this activity. The ATL machine cannot read profiles like metamodels.

The Matlab script is generated using Simulink and Stateflow APIs to generate functional block diagrams and state machine diagram respectively. Running the script on the Matlab platform a Simulink model can be created.

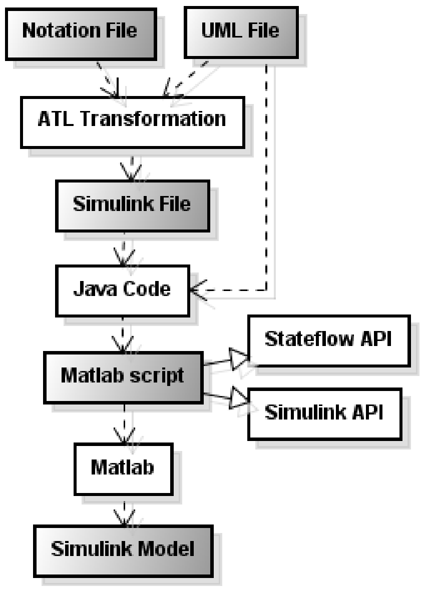


Figure 5: Artifact generation sequence of the transformation process.

4 AN APPLICATION EXAMPLE OF THE SYMPLES TRANSFORMATION PROCESS

An application example is presented as a proof of concept of the transformation process based on part of the autopilot Yapa 2 (YAPA 2011). The autopilot software runs in a controller board for Paparazzi UAVs.

Initially the dynamics of aircraft movements were analyzed. Based on the flight controller system of Yapa 2, a SyMPLES model was created to handle hypothetical commands generated by the autopilot. This example shows the generated artifacts produced by the transformation process and a simulation of the Simulink model.

4.1 Flight Controller System

A Flight Control System reads information from the sensors and guides the UAV to follow its predefined plan. Its main components are sensors and the autopilot (FAA 2008). In a typical cruise flight, the UAV operates at a desired flight condition and reaches the navigation points (waypoints) through roll commands, however, the airspeed and altitudes are fixed.

One objective of the flight controller is to process flight commands generated by the navigation system. It is divided into two main controls, one to control vertical (altitude) and one horizontal (navigation), which generate controls to the servos.

4.2 SysML Flight Control

An example of a flight controller for UAVs Paparazzi-type fixed-wing aircraft is presented. The

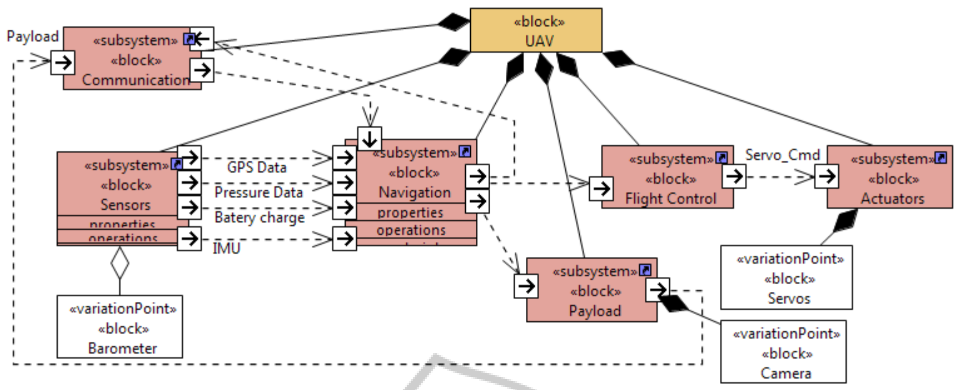


Figure 6: Initial Yapa 2 SPL architecture represented in SysML.

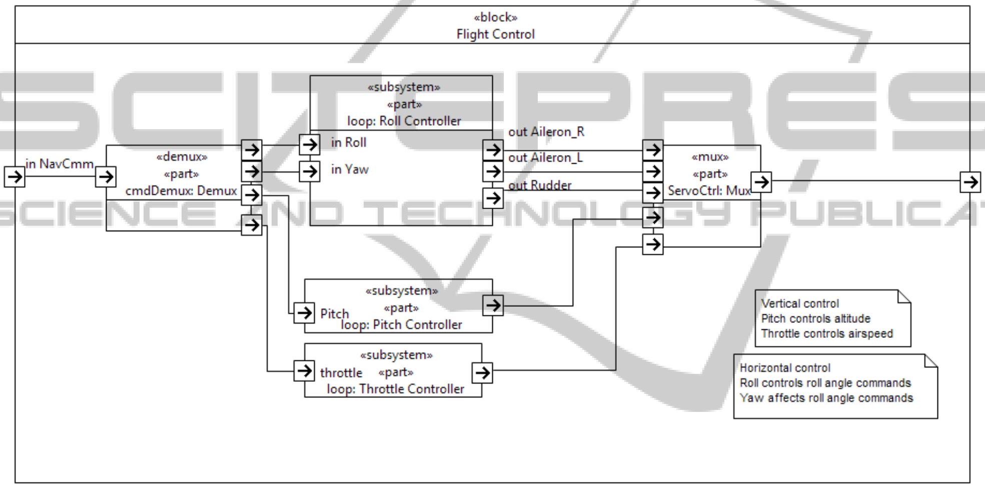


Figure 7: Internal block diagram for flight control.

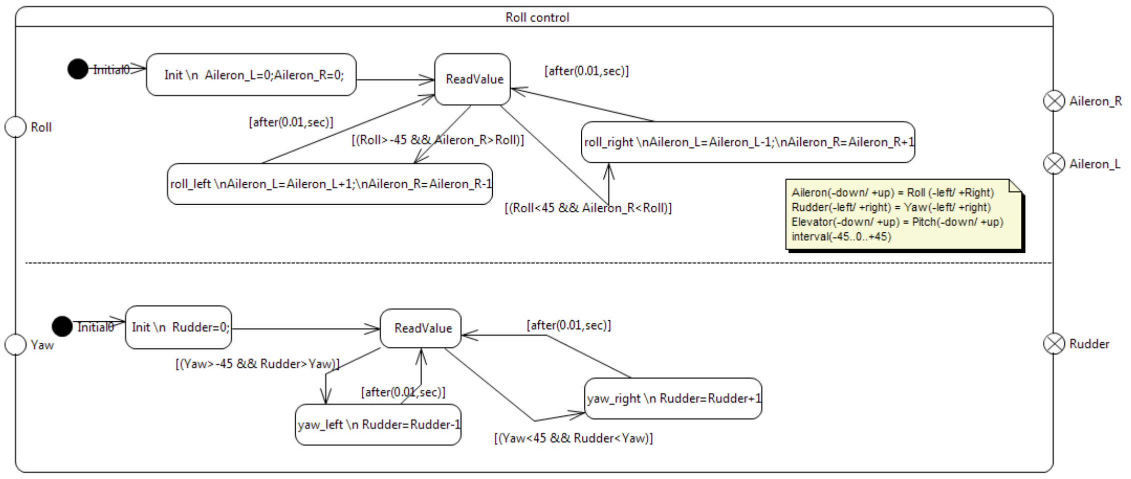

Roll control
Initial0
Init \n Aileron_L=0;Aileron_R=0;
ReadValue
[after(0.01,sec)]
Roll
[after(0.01,sec)]
[(Roll>-45 && Aileron_R>Roll)]
roll_right \nAileron_L=Aileron_L-1;\nAileron_R=Aileron_R+1
roll_left \nAileron_L=Aileron_L+1;\nAileron_R=Aileron_R-1
[(Roll<45 && Aileron_R<Roll)]
Aileron_R
Aileron_L
Aileron(-down/ +up) = Roll (-left/ +Right)
Rudder(-left/ +right) = Yaw(-left/ +right)
Elevator(-down/ +up) = Pitch(-down/ +up)
interval(-45..0..+45)
Initial0
Init \n Rudder=0;
ReadValue
[after(0.01,sec)]
Yaw
[(Yaw>-45 && Rudder>Yaw)]
[after(0.01,sec)]
yaw_left \n Rudder=Rudder-1
yaw_right \n Rudder=Rudder+1
[(Yaw<45 && Rudder<Yaw)]
Rudder

Figure 8: State machine diagram for roll controller.

SysML diagrams were specified based on the horizontal control of Yapa 2 autopilot. The Yapa 2 model was created by the SyMPLES processes and represented with the support of Papyrus tool.

Figure 6 shows an example of an initial SPL architecture for the Yapa 2 autopilot. The architecture is represented by a SysML block definition diagram. Blocks with stereotypes <<subsystem>> are mapped to subsystems in Simulink. <<variationPoint>> stereotypes represent elements that have variants to be resolved in the SyMPLES SPL. Subsystems are connected through its ports.

Figure 7 shows the flight control subsystem represented by a SysML internal block diagram. The diagram is composed of horizontal (controller roll) and vertical motion controllers (pitch and throttle controllers). Some navigation commands are processed by the element `loop: Roll Controller` that controls roll and yaw movements using ailerons and rudder servos.

Figure 8 shows an example of a state machine diagram created to the element `loop: Roll Controller`. In this example, values are set to the actuators according to the roll or yaw commands received by the navigation subsystem. It is assumed a fixed range of values that varies from -45 to +45 (degrees) to input commands and output (servos). This range of values was used to simplify the example. The states are named with expressions in which the symbol "\ n" represents a line break that is used to differentiate the state name and the assignment of values in Stateflow model. Transitions are represented by conditional expressions in which input values and local variables are checked. When a state is reached, servo values are increased or decreased.

4.3 Simulink Flight Control

The flight controller for Simulink was generated according to the transformation process. The Simulink model was generated by running the Matlab script. Figure 9 shows the initial architecture transformed to Simulink based on the Block Definition diagram for Yapa 2 (Figure 6). Only elements with stereotypes of the SyMPLES-

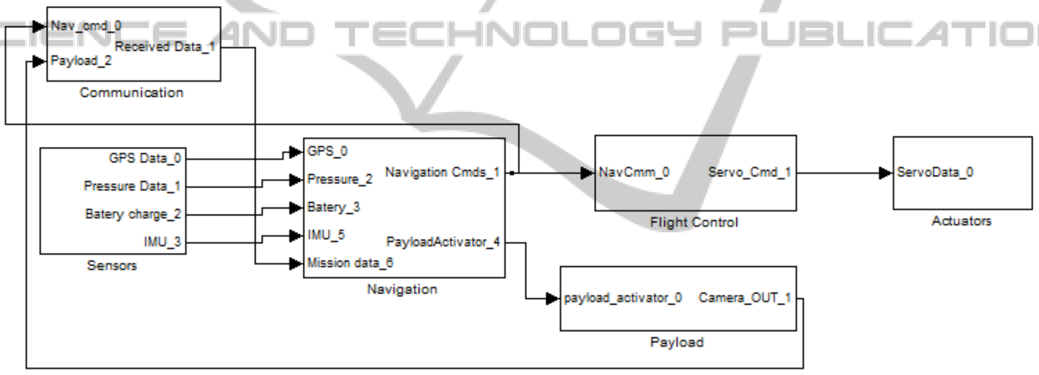


Figure 9: Initial Yapa 2 architecture generated to Simulink.

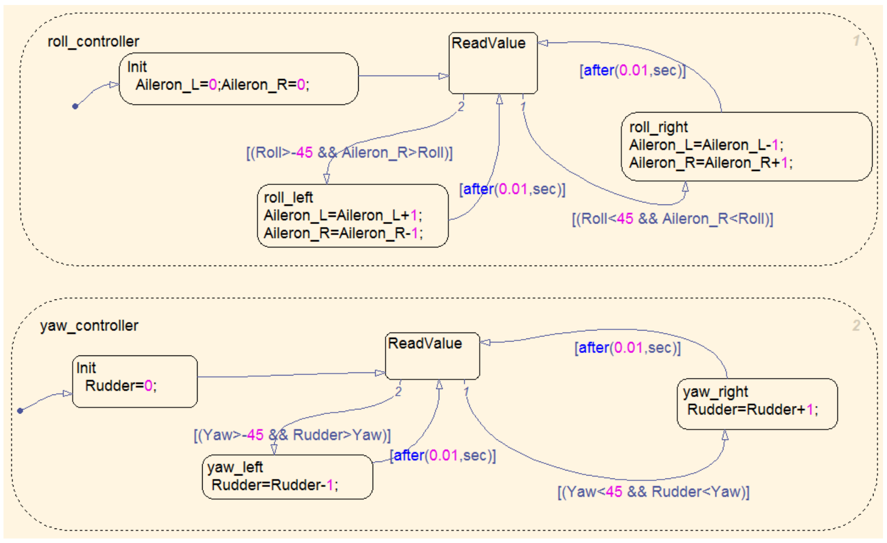


Figure 10: Stateflow diagram generated from roll controller.

ProfileFB are considered in the transformation. The connectors are processed only if the subsystems that send and receive data have ports that are connected.

Figure 10 shows the state machine diagram transformed to Stateflow in Simulink (Figure 8). In this example, the name of the state is defined by the first line and subsequent assignments are the setting values for the servos commands.

4.4 Simulink Flight Control Simulation

Extra elements are added to allow the simulation of roll control in the Simulink model of the flight control generated. Test cases can be added to the model using Simulink functional blocks named signal builder. One signal builder was created to simulate possible signals generated by the autopilot. These signals include roll, yaw, pitch and throttle commands. Figure 11 shows an example for the commands created by the signal generator. At the second 10, the autopilot sends a command signal "Roll 45" and "Pitch 45". The command roll is updated and is gradually decreased until the value -45 in the second 35. Then, it generates the command "Roll 45". The behavior of this signal is to simulate the sliding of a joystick.

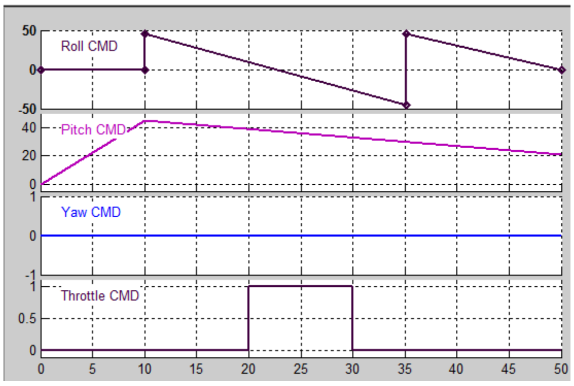


Figure 11: Example of commands generated from autopilot.

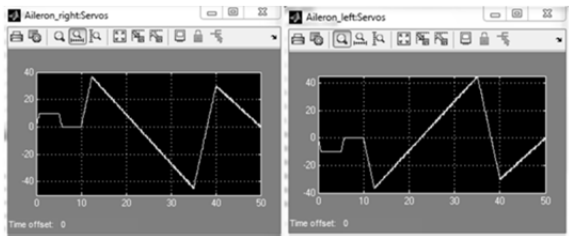


Figure 12: Visual result of ailerons command values.

Figure 12 visually shows the simulation results for the servos "Aileron_right" and "Aileron_left". The command "Roll 10" was sent in the first 5 seconds simulating manual commands. Then the autopilot signals of Figure 10 are sent to the controller roll that set the values of servos to perform the movement. At the second 10, the command "Roll 45" must perform the right roll movement and the right aileron must go up while the left go down.

5 DISCUSSION AND RELATED WORK

Some studies apply a transformation process from UML to Simulink models. In Sjöstedt et al. (2008) the transformation of Simulink models to UML is performed. Using a Simulink model, a XMI file is generated from the execution of a program implemented in the Java language. The XMI file is used to generate UML activities diagrams from an ATL transformation. However, the applied domain is different from that shown in this work. Moreover the transformation is not applied to a SPL as SyMPLES.

Biehl et al. (2010) presents a solution for the domain of automobiles, which defines a process of bidirectional transformation between Simulink models and a UML extension called EAST-ADL. However, this work considers only the domain of automotive systems without a SPL as defined by SyMPLES.

Brisolara (2007) presents a transformation process from UML to Simulink models, but this work uses UML activity diagrams as input. In our work block definition, internal block and state machine diagrams are used as input to the transformation process.

6 CONCLUSIONS AND FUTURE WORK

The SyMPLES transformation process focused on the application engineering of a SPL, based on MDE techniques. This supports the generation of platform-specific models of SPL through the refinement of abstractions which facilitates code generation. SysML configured models are used as input for transformation process and represent embedded systems at the initial levels of development. The SyMPLES-ProfileFB was extended to allow the mapping and transformation of the models. The process was evaluated by the controller board Yapa 2.

There are some limitations in the transformation process: (i) initially only a set of Simulink functional blocks are mapped by SyMPLES-ProfileFB stereotypes. We have considered mainly functional blocks related to the development of UAVs; and (ii) initially only block definition, internal block and state machine diagrams were used in the transformation process.

Future works includes the use of additional SysML diagrams in the transformation, and the extension of the SyMPLES-ProfileFB to support more functional blocks to others domains.

ACKNOWLEDGEMENTS

We are grateful to the Brazilian funding agencies CNPq/INCT-SEC and FAPESP for supporting this work.

REFERENCES

Biehl, M., Sjöstedt, C.-J. & Törngren, M., 2010. A modular tool integration approach : experiences from two case studies. *3rd Workshop on Model-driven tool and Process Integration (MDTPI2010)*.

Braga, R. et al., 2011. Evolving Tiriba Design towards a Product line of Small Eletric-Powered UAVs. In *1st Brazilian Conference on Critical Embedded Systems*. pp. 63–72.

Brisolara, L. B., 2007. *Strategies for Embedded Software Development Based on High-level Models*. UFRGS - Porto Alegre.

Burch, J. R., Passerone, R. & Sangiovanni-Vincentelli, A. L., 2001. Using Multiple Levels of Abstractions in Embedded Software Design. In T. A. Henzinger & C. M. Kirsch, eds. *International Workshop on Embedded Software*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 324–343.

Czarnecki, K. & Helsen, S., 2003. Classification of Model Transformation Approaches. In *OOPSLA'03 Workshop on the Generative Techniques in the Context of Model-Driven Architecture*. Anaheim, California, USA, p. 17.

Ebert, C. & Jones, C., 2009. Embedded Software: Facts, Figures, and Future. *Computer*, 42(4), pp.42–52.

EMF, 2012. Eclipse Modeling Framework Project. Available at: http://www.eclipse.org/modeling/emf/.

FAA, F. A. A., 2008. Flight Controls. In *Pilot's Handbook of Aeronautical Knowledge*. p. 12.

Fragal, V., Junior, E. & Gimenes, I., 2011. Mapping Software Product Line Features to Unmanned Aerial Vehicle Models. In *1st Brazilian Conference on Critical Embedded Systems*. pp. 49–54.

Hunter, A., 2012. Graphical Modeling Framework (GMF) Notation. Available at: http://www.eclipse.org/projects/project.php?id=modeling.gmp.gmf-notation.

Linden, F., Schmif, K. & Rommes, E., 2007. *Software Product Lines in Action*, Springer.

Lykins, F. M., 2000. Adapting UML for an Object-Oriented Systems Engineering Method (OOSEM). In *INCOSE International Symposium*.

Marwedel, P., 2010. *Embedded System Design: Embedded Systems Foundations of Cyber-Physical Systems*, Springer; 2nd ed. 2011 edition (December 3, 2010).

Obeo, 2006. Atlas Transformation Language. Available at: http://www.obeo.fr/pages/atl-pro/en.

Oliveira, E. A. J., Gimenes, I. M. S. & Maldonado, J.C., 2010. Systematic Management of Variability in UML-based Software Product Lines. *Journal of Universal Computer Science*, 16, pp.2374–2393.

OMG, 2006. Diagram Interchange. *OMG*, p.86. Available at: http://www.omg.org/cgi-bin/doc?formal/06-04-04 [Accessed October 11, 2012].

Papyrus, 2012. Open Source Tool for Graphical UML2 Modelling. Available at: http://www.papyrusuml.org/scripts/home/publigen/content/templates/show.asp?P=128&L=EN&ITEMID=12.

Pastor, E., Lopez, J. & Royo, P., 2006. An Embedded Architecture for Mission Control of Unmanned Aerial Vehicles. In *9th EUROMICRO Conference on Digital System Design (DSD'06)*. IEEE, pp. 554–560. Available at: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1690087 [Accessed December 12, 2012].

Polzer, A., Kowalewski, S. & Botterweck, G., 2009. Applying software product line techniques in model-based embedded systems engineering. In *2009 ICSE Workshop on Model-Based Methodologies for Pervasive and Embedded Software*. IEEE, pp. 2–10.

Ruscio, D., 2007. *Specification of model transformation and weaving in model driven engineering*. Università di L'Aquila. Available at: http://www.di.univaq.it/diruscio/PhDThesis_DiRuscio.pdf.

Silva, R. F., 2012. *SyMPLES : Uma Abordagem de Desenvolvimento de Linha de Produto para Sistemas Embarcados baseada em SysML*. Universidade Estadual de Maringá.

Simulink, 1994. Simulation and Model-Based Design. Available at: http://www.mathworks.com/products/simulink/.

Simulink Coder, 2012. Real-Time Workshop. Available at: http://www.mathworks.com/products/simulink-coder/index.html.

Sjöstedt, C.-J. et al., 2008. Mapping Simulink to UML in the design of embedded systems:Investigating scenarios and transformations. In *OMER4 Post-proceedings, 2008*. pp. 137–160.

Steiner, E. M., 2012. *Gerenciamento de configuração de uma linha de produtos de software de veículos aéreos não tripulados*. USP.

SysML, 2008. OMG Systems Modeling Language. *OMG*, p.234.

TOPCASED, 2012. The Open-Source Toolkit for Critical Systems. Available at: http://www.topcased.org/.

YAPA, 2011. YetAnotherPaparazziAutopilot v2. Available at: http://paparazzi.enac.fr/wiki/YAPA/v2.0.