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INTERDISCIPLINARY SYSTEM MODEL FOR AGENT BASED MECHATRONIC DESIGN OF TURBOCHARING SYSTEMS

J. Schmelcher, R. Stetter, A. Kaufmann and H. Voos

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1. Introduction

The advances in technology and science lead to the creation of mechatronic systems with increasing complexity. Due to this rising complexity of the systems to be developed, the requirements towards the development processes are ascending in the same manner. As a result of the historical evolution of the involved domains (mechanical engineering, electrical engineering and computer science), the specific IT-Tools were not designed for interdisciplinary processes and can usually even barely exchange data among each other. This causes a lack of interoperability and results in ineffective development processes with drawbacks on the consistency of interdisciplinary model data. To deal with this situation, research and industry encouraged the idea of a domain-spanning system model, which contains the cross-domain information and important relations (e. g. [Chen et al. 2009]). One promising approach to survey these interdisciplinary information and relations and thus help the people participating in the design process is based on multi-agent systems. The basis on which a multi-agent system is able to make decisions concerning the cross-domain information and relations can be a model of the mechatronic system modelled with the modelling language SysML. This paper will present an approach how this system models can be developed using the modelling language SysML and furthermore it will expound a practical model of a real mechatronic system – a turbocharging system for a car engine. Accordingly, the paper is divided into two main sections. Section 2 gives an overview of agent based systems in general and the modelling language SysML and its possibilities in modelling mechatronic systems, whereas section 3 presents the model of a real mechatronic system. To point out the potential of such system models, an example, also in chapter 3, describes the effects on the system model caused by changes in a particular part of the model.

2. Theorethical background

2.1 Agent based systems

Due to the high innovation potential of mechatronic systems such systems gained a great importance in industry and complex systems containing the fields of mechanical engineering, electrical engineering and information technology are composed. The development of such complex systems poses great demands on the involved engineers. To cope with this increasing complexity the VDI-guideline 2206 was developed, which is based on the V-model commonly used in the software development. This guideline represents the state of the art in the development of mechatronic systems. However, this VDI-guideline does not directly propose any interdisciplinary product models and tools. A promising approach to realize interdisciplinary process is the use of intelligent software agents [Stetter and Voos 2010]. To judge this estimation the development process of mechatronic systems has to be examined more closely. In all involved disciplines different IT-Tools can be identified, which are very specialized and optimized for their intended use. But this specialisation hinders the development process of mechatronic systems because of the missing or poor capabilities of the tools to exchange data (usually interface format are available but data quality and integrity are greatly reduced and the possibilities for further editing are limited). A solution for this problem could consist of systems of multiple agents. As [Weiss 1999] points out, an agent represents a computer system which can act freely in its specific environment considering the goals of the system.

Therefore multi-agent-systems could handle the task to supervise the interrelationships and interdependencies of a mechatronic system. An overview of the state of the art in agent-based systems can be found for instance in [Weiss 1999], [Luck and d'Inverno 2001] and [Trencansky and Cervenka 2005]. For the agent system's capability to support the development of mechatronic systems it is necessary to develop a domain-spanning model of the desired system. This model forms the framework in which the agent system is able to act and supervises the development process of mechatronic systems. Therefore the domain-spanning model must contain the correlation and interdependencies as well as their impacts on the system. In order that the agent system can deal with the domain-spanning model, it has to be split so one agent has only one correlation of the whole system to monitor. The support in the development process of mechatronic systems persists in the analysis of changes to components and their effect on the whole system so that the respective agent can be informed. This agent has to notify the particular engineer and tells him how these changes influence his field of action. A concept for the implementation of agent based systems was developed and presented in detail by [Stetter et al. 2011] – see Figure 1; they also propose SysML for systems modelling.

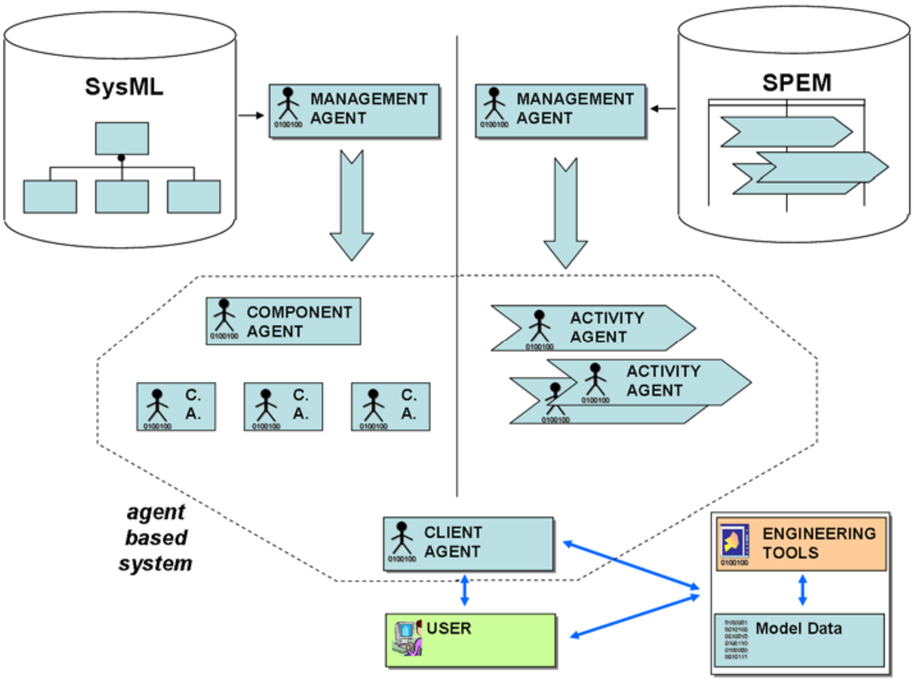

Figure 1. Agents based systems architecture [Stetter et al. 2011]

2.2 SysML

The modelling language used for the creation of the domain-spanning model is the *System Modeling Language (SysML)*, which was developed in 2001 in collaboration of the *Object Management Group* with the *International Council on Systems Engineering.* The development of the SysML was based on the *Unified Modeling Language 2.1.1* which is already established in software development. Since the SysML is related with the UML 2.1.1, both have some elements in common, however the SysML has in addition several elements specialized for the field of systems engineering. As the system engineering is faced with "the preparation of a system design and the verification of the system as to compliance with the requirements, taking the overall problem into account" [Weilkiens 2007], it is obvious that the SysML can be used for creating the domain-spanning model. For modelling any imaginable system, the SysML offers a wide range of possibilities, but for the systematic handling of the domain-spanning model through the use of agents only a limited scope is used. Nevertheless it is possible to model any imaginable system using the *block definition diagram*, the *internal block diagram* and the *parametric diagram* with its corresponding model elements ([Stetter et al. 2011] – examples of block diagrams are shown in Figure 2).

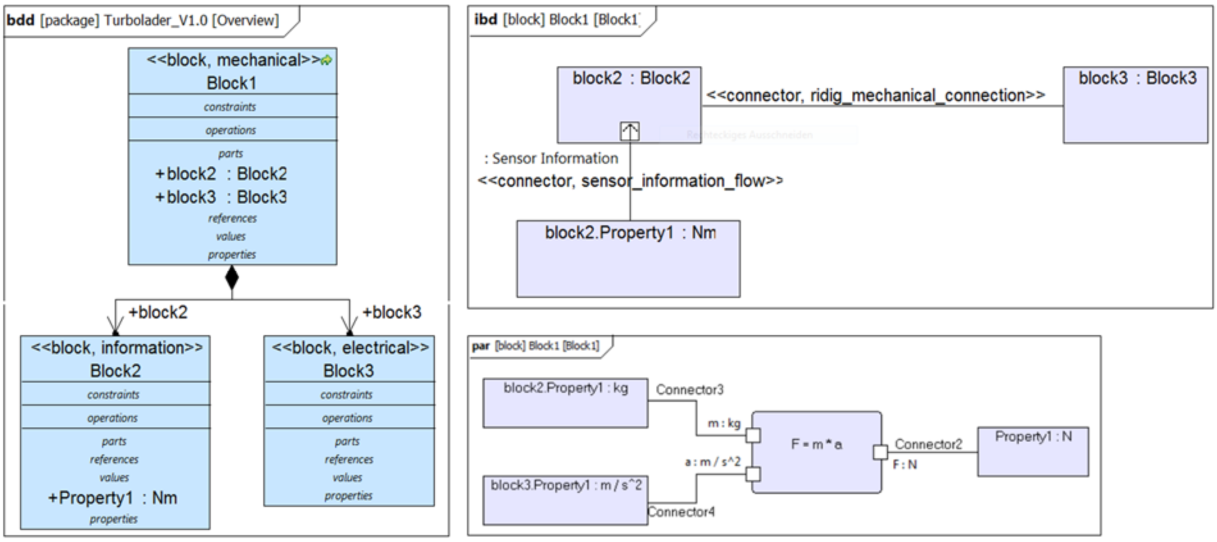

Figure 2. Exemplary diagrams: block definition diagram (bdd), internal block diagram (ibd) and parametric diagram (par)

2.2.1 Block definition diagram (bdd)

The *block definition diagram* represents the topmost level of the domain-spanning system model and contains the different components used for the creation of a mechatronic system. These components are modelled as so-called *blocks* and they can serve for representing the physical structure of a system. To indicate the hierarchical structure of the components to each other, so-called *compositions* are used. In the block definition diagram of Figure 2 it is obvious that Block1 features the topmost hierarchically level and the Block2 and Block3 are assigned to it as parts through the use of compositions. The plus-sign and the word in lowercase next to the compositions mark the role of the inferior block which he is playing for the superior block. So it is thinkable that in a model of an aircraft owning two identical engines one is assigned to the role +*engine_left* and the other to the role +*engine_right*. Furthermore the allocation of a property to Block2 can be seen which is divided into two partitions. The first partition indicates the name of the value and the second partition is separated by a colon and names the unit of the value, the so-called *Value Typ*.

2.2.2 Internal block diagram (ibd)

The *internal block diagram* offers the possibility to extend the hierarchical structure modelled in the block definition diagram by the physical and logical structure of the blocks to each other. For this purpose the blocks themselves are not used, but the *parts* or *values* connected to the block for which the internal block diagram is created. By using the *binding connector* it is possible to visualize connections as well as matter flows, energy flows or information flows. For visualizing the last mentioned the parts have to be equipped with so-called *ports* indicating the interfaces between component boundaries. To characterise the port it is necessary to define an interface and allocate it to the desired port. The internal block diagram in Figure 2 shows two parts connected with a binding connector. This connector between the parts Block2 and Block3 could be for instance a rigid mechanical connection. In turn the binding connector between the part Block2 and the value Property1 indicates a flow of information, exchanging information via a port with the interface *information*.

2.2.3 Parametric diagram (par)

The *parametric diagram* features, in contrast to the two other diagrams, the ability to integrate physical principles or logical correlations into the domain-spanning system model. Therefore the *constraint properties* of the *constraint blocks*, located for instance in a library, are used. These constraint properties form a mathematical equation like y = f(x), which contains the parameters y and x. For the correct definition of the constraint block, the parameters have to be assigned to it as properties. In the parametric diagram the *constraint property* can be identified through its rounded corners and the little rectangles attached to it which are indicating *properties*. In the parametric diagram of Figure 2 the computation of Newton's second law can be seen. The properties of the blocks 2 and 3 represent the input variables which are handed over by a binding connector to the properties, the little rectangles, of the constraint property. The task of the constraint property itself is to compute the equation and pass it over via a property to the property 1 with the unit N.

3. Application example: Turbocharging system

After the brief introduction in which the theoretical background in creating domain-spanning system models was explained, the following section will deal with a practical example. This example contains a turbocharging system for a car engine which can be understood as a mechatronic system (this statement is elucidated in this section). The example intends to show the structure and the concrete application and its benefits for the development process.

3.1 Turbocharging system for a car engine

Due to the energy efficiency potential due to downsized engines, turbocharging systems are nowadays present in most cars. A car turbocharger consists of a radial flow turbine and a radial compressor which are mounted on one axle. These main components of the turbocharger have no mechanical connection to the combustion engine but a thermo-dynamic one. The radial compressor is driven by the radial flow turbine, which converts the enthalpy from the hot exhaust gases into rotational mechanical energy. As a result of the balance of power generation of the turbine and power consumption of the compressor, a specific rotational speed of the turbocharger will appear which is independent from the one of the combustion engine [Robert Bosch GmbH 2011]. The specific rotational speed of the radial turbine respectively the radial compressor leads to an intake and a compression of fresh air in the cylinder. As a consequence, the pressure in the cylinder rises and a higher amount of oxygen is available for the combustion process. Due to the proportional correlations between the pressure in the cylinder, the mean effective pressure and the engine power, an increased engine power can be achieved and thus smaller, more fuel efficient engines can be applied to a given application.

Considering the characteristic of the combustion engine and the turbocharger, it is obviously that closed loop control systems are needed to avoid damages of the combustion engine or the turbocharger. The raising pressure in the cylinder will increase the flow of enthalpy contained in the exhaust gases and in turn the higher enthalpy will lead to an increased rotational speed of the turbocharger. So either the combustion engine will be damaged due to too high pressures in the cylinder or the turbocharger will be damaged due to excessive centrifugal forces resulting of the high rotational speeds. Three different possibilities for restricting the pressure in the cylinder are commonly used:

- variable slider ring turbine,
- variable nozzle turbocharger and
- wastegated turbocharger.

All three possibilities have the goal in common to reduce the rotational speed of the radial flow turbine in order to decrease the pressure in the cylinder [Robert Bosch GmbH 2004]. This paper focuses on the boost-pressure control by means of a bypass- or wastegate-valve. The purpose of this valve is to bypass the radial flow turbine in order to reduce the flow of enthalpy so that the rotational speed will either decrease or remain constant. The activation of the wastegate-valve in a pneumatic manner is state of the art. But new developments focus on the implementation of electrical actuators for manipulating the valve in order to make the control behaviour more precise and faster [Robert Bosch GmbH 2011] – see Figure 3.

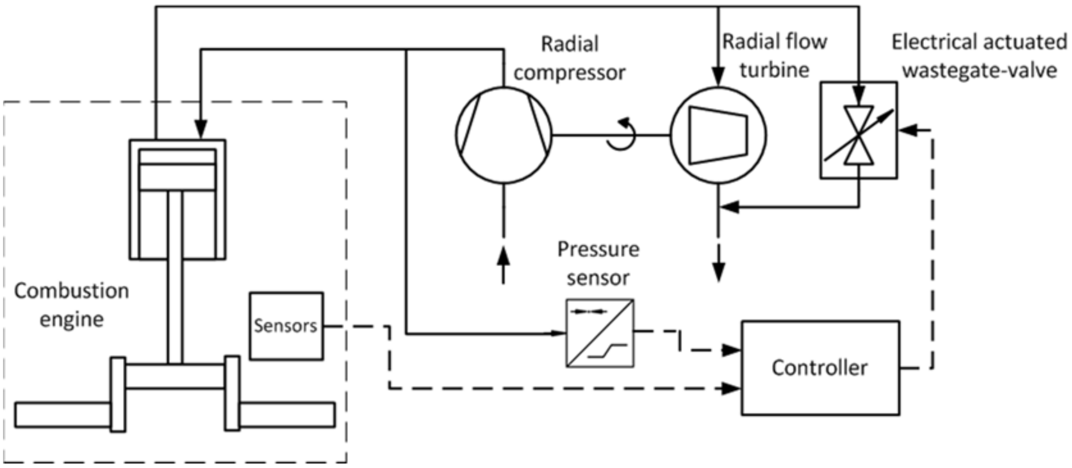

Figure 3. Functional principle of a turbocharging system

Therefore it is necessary to compute a desired angle of the wastegate-valve through the use of engine data and measurements. The interaction of pressure- and temperature sensors, electrical actuators, control systems and mechanical components meets the requirements to be treated as a mechatronic system.

In order to work out the physical relationships needed for modelling the system model, two MS Excel-files could be developed. One file contains a parametric design process which computes the shape of the turbine and compressor wheel, subjected to a desired engine map. To complete the design process, the calculated shape is automatically handed over to the CAD-program Pro/ENGINEER so that a new CAD-model can be created without manual actions (Figure 4). The other file computes the angle of the wastegate-valve which is dependent on the designated boost-pressure.

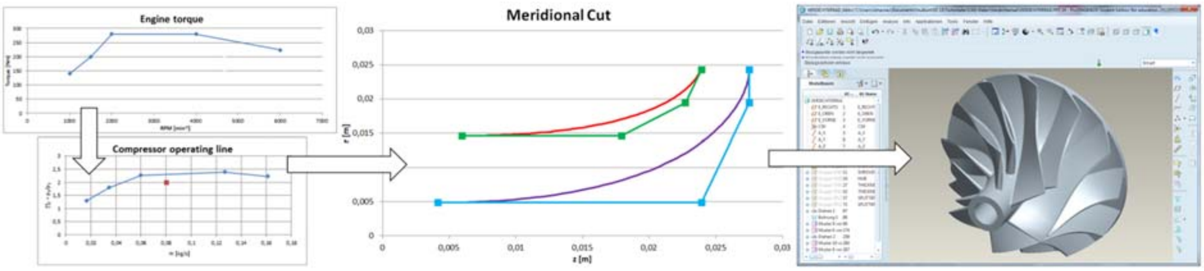

Figure 4. Parametric development of the geometry of turbocharger components

3.1.1 Physical structure

To model the different components and the relations between them, multiple block definition diagrams and one internal block diagram are used. The first step in creating the system model of the turbocharger is to construct the block definition diagram showing the hierarchically structure of the involved systems. Due to the fact that the turbocharger cannot exist without interacting with other components of the combustion engine, the top level of the block definition diagram represents the overall system in which the turbocharger is embedded.

One level beneath the block *turbo engine* other blocks can be found which represent the systems necessary for the correct modelling of the system model of the turbocharger. These blocks respectively systems are:

- the *combustion engine* with its subsystems intake and exhaust system

- a *control system* for monitoring the pressure in the cylinder and
- the *turbocharger* with its mechanical parts and an electrical actuator for manipulating the wastegate-valve.

The assignment of these blocks to the topmost block *turbo engine* is done through the use of compositions which label the role the inferior block plays for the superior. Since no block is used repeatedly, systematic roles are not necessary to distinguish among the systems. To make the block definition diagrams more clearly, not all information are presented in one diagram, so several diagrams are used to present a specific point of view onto the system to be modelled (Figure 5).

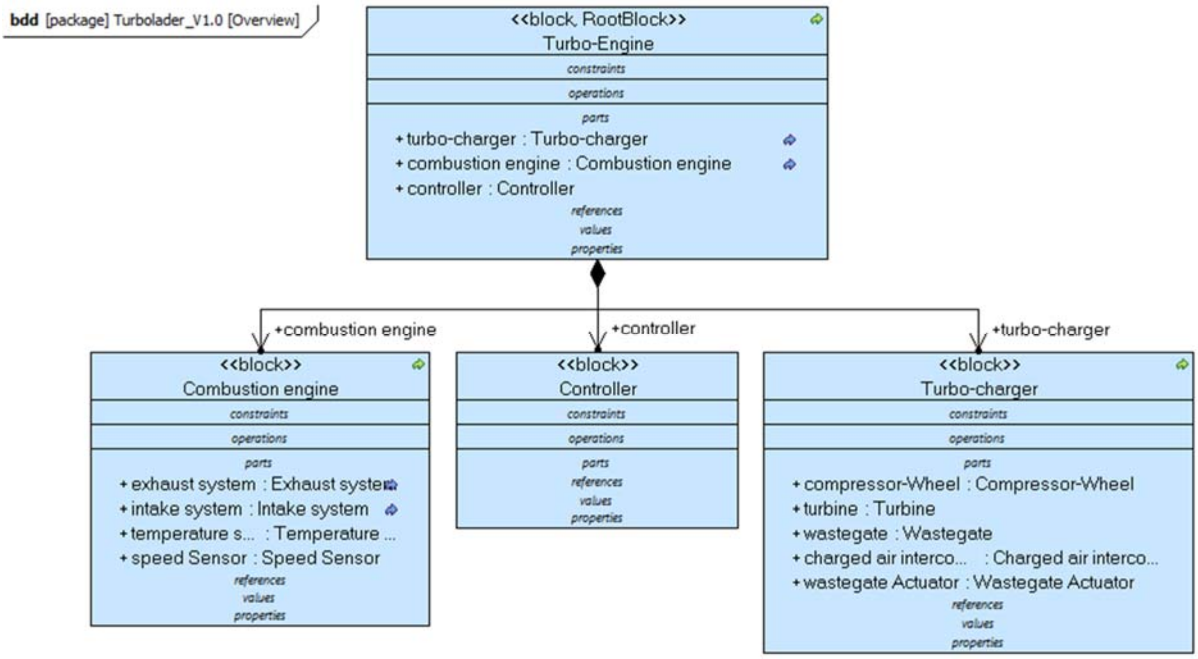

Figure 5. Block definition diagram of the topmost block *turbo engine*

Therefore the uppermost block definition diagram contains only the involved systems which are necessary for modelling the mechatronic system of the turbocharger. To give a detailed insight into the involved systems, each system owns a block definition diagram which contains its components and subsystems. The block definition diagram which describes in detail the combustion engine consists of the blocks for the intake and exhaust system and two blocks for a temperature and a speed sensor. The lowest level contains the components of the intake and exhaust system. It depends on the particular system if it is useful to add a subsystem level or not. Here it is helpful to add the subsystem level of the intake and exhaust system because of the possibility to enhance the model in a modular manner. Due to the lack of complexity the block definition diagram of the turbocharger consists only of the components and not of other subsystems.

After the hierarchical structure has been established, the structure of the components among each other can be developed. Since the complexity of the systems turbocharger and intake and exhaust system is rather low, they do not have their own internal block diagram. Therefore the physical structure is depicted in one internal block diagram which owns all the information concerning the several systems. To have access to the required properties the internal block diagram is deposited at the topmost block of the SysML-model (Figure 6).

The intention of this diagram is to visualize the energy flow and the closed-loop control of the wastegate-valve. However pure aspects of mechanical engineering or thermodynamics do not find consideration in the internal block diagram because of their significance in their domain specific IT-tools. So the focus is on the visualization of the domain-spanning aspects like the air-mass flow through the combustion engine and the turbocharger. The internal block diagram contains the single components of the turbocharger as well as the intake and exhaust system which are connected through binding connectors. However these binding connectors do not represent a mechanical connection but the air-mass flow with its specific enthalpy content. Between the properties *Raw air pipe* and *Compressor-Wheel* are binding connectors existing which indicate the flow of fresh air. To reveal that this flow of fresh air has a low energy content stereotypes are used. The contained energy content can be heightened due to the radial compressor and therefore the binding connectors between the properties *Compressor-Wheel* and *Combustion Engine* are characterised with the stereotypes *high_energy_flow_fresh_air*. The processes in the combustion engine are not part of the SysML-model and thus it is treated as a black box which converts the fresh air into hot exhaust gases also with high energy content. These hot exhaust gases flow either through the radial flow turbine into the bifurcated front pipe or bypasses the turbine through the wastegate-valve. The flow path is indicated using binding connectors with the stereotype *high_energy_flow_exhaust_gas*. The further way of the exhaust gases to the rear exhaust pipe is visualized using binding connectors characterized with the stereotype *low_energy_flow_exhaust_gas*.

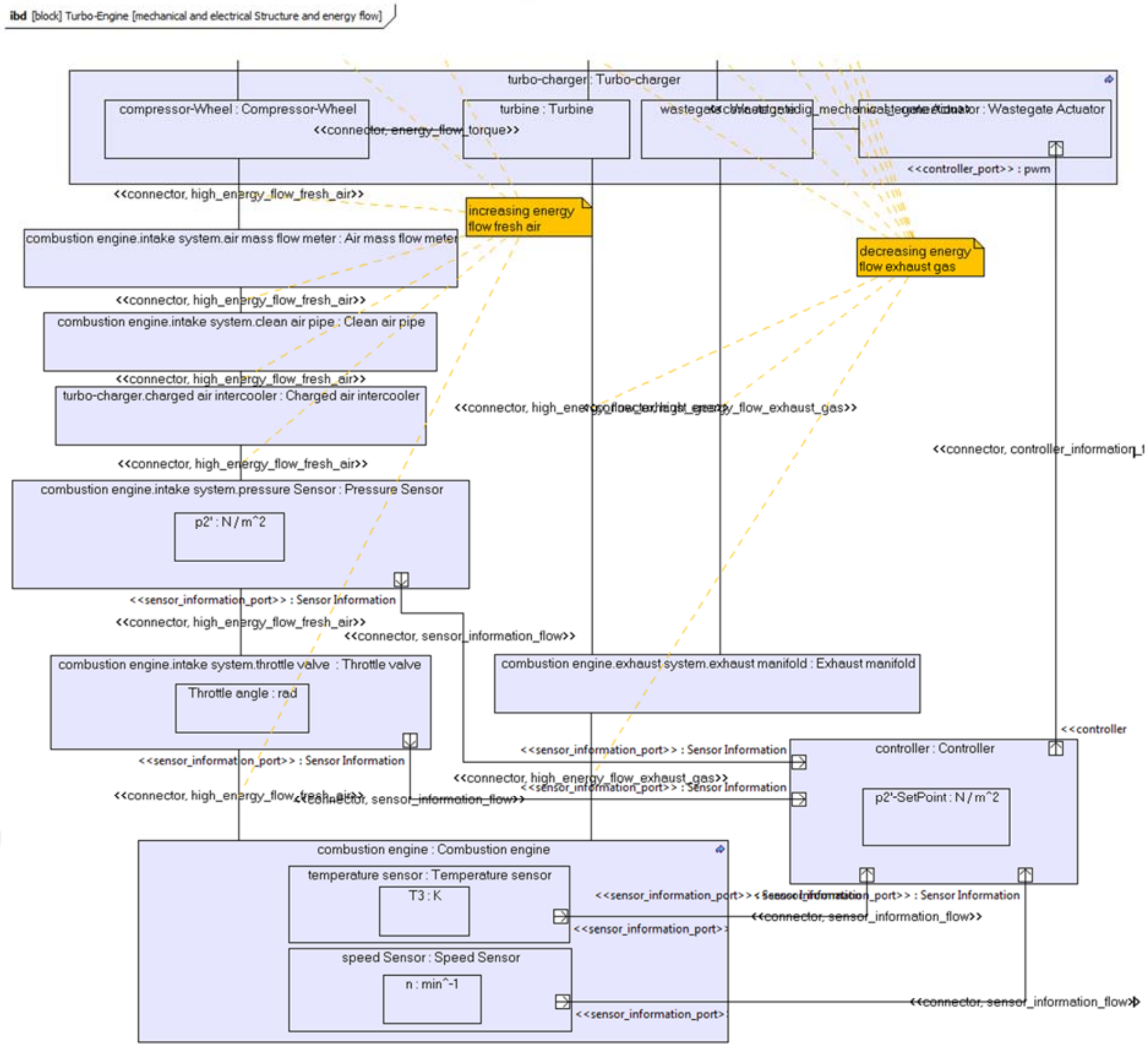

Figure 6. Internal block diagram - showing the structure of the components to each other

Furthermore the mechanical structure of the turbocharger is displayed through the use of binding connectors. They indicate the mechanical connection of the radial flow turbine and the radial compressor as well as the connection of the actuator with the wastegate. For piloting the actuator a control system is used which computes the control signal on the basis of measurements and constants.

The measurements are recorded by sensors and submitted to the control systems through ports and binding connectors. To distinguish these binding connectors from the others, they are characterized using the stereotypes *sensor_information_flow* and *controller_information_flow*.

3.1.2 Logical structure

For visualizing physical correlations and mathematical computations the parametric diagram with its domain-spanning significance is used. Due to the complexity of mechatronic systems several parametric diagrams have to be employed in order to format the corresponding information. To illustrate the calculations taking place in the control system one particular parametric diagram for instance is required. The point of origin for those calculations is the throttle-angle, which is proportional to the torque generated by the combustion engine. Besides other engine data this torque is assigned to the constraint property, responsible for the computation of the pressure after the intercooler. This is the desired pressure which should be achieved through the closed-loop control of the wastegate-valve. Therefore this pressure is subtracted from the pressure measured after the intercooler for calculating the system deviation. For counteracting the system deviation it is assigned to a PID-Controller and afterwards the control signal is assigned to a constraint property. This constraint property represents the calculation of the desired angle of the wastegate-valve which is done in MS Excel and then the resulting angle is passed to another constraint property. The task of the constraint property is to convert the angle into a control signal for the actuator of the wastegate-valve. The basic idea of the presented parametric diagram is to visualize the control process with their goal to influence the angle of the Wastegate-valve in order to adjust the pressure after the intercooler. One aspect is that the properties respectively the components involved in the closed-loop control are visible. Another aspect is that for purposes of simulating the closed-loop control distinctive properties can be passed over to MATLAB Simulink.

Another parametric diagram is used to visualize the design process of the radial flow turbine. The design process uses the method of a mid-section design, where the most prominent dimensions of the turbine wheel are calculated. The result depends on some experienced data, on the condition prevailing after the combustion process and on the air-mass flow through the combustion engine. In the process of calculation several intermediate results like velocities, temperatures and pressures at distinctive point of the turbine wheel are computed. The final results are the inner and outer diameter at the outlet section and the diameter and the width at the inlet section. Since different parameters are used for the design process of the radial flow turbine and of the radial compressor which have their origin in the engine development, changes of these parameters also affect the turbine and the compressor. Examples for these domain-spanning contexts are the total pressure and the total temperature before the inlet section of the turbine. They are depending on the temperature and the pressure acting after the combustion process of the engine and also on the losses in the exhaust manifold. For illustrating theses dependencies a particular parametric diagram exists, showing the calculation of the accordant parameters. The idea of visualizing the mid-section design process in a parametric diagram is to show the interdisciplinary connections and to identify the parameters which have effect on other domains than their own.

Besides the two presented parametric diagram, there are other diagrams to describe the further interrelationships of the mechatronic system turbocharger. One diagram is similar to the one of the mid-section design process of the radial flow turbine, though this diagram visualizes the design process for the radial compressor. And finally two diagrams are used to take the losses of temperature and pressure into account and to compute the desired air-mass flow utilized for the design process of the radial flow turbine and the radial compressor.

The complexity and the quantity of the parametric diagrams compared to the single internal block diagram show the importance of these diagrams for the quality and the information content for the overall SysML-model.

3.1.3 Example of use

The domain-spanning approach of this SysML-model can be pointed out through the use of an example. Therefore it is assumed that the air filter in the intake system of the combustion engine and the charge air intercooler had been changed. Due to the modifications to the air filter, its temperature and pressure losses are affected whereas the modifications to the charge air intercooler will change its outlet temperature. To understand the influences of these alterations the corresponding diagrams will be examined more closely (Figure7).

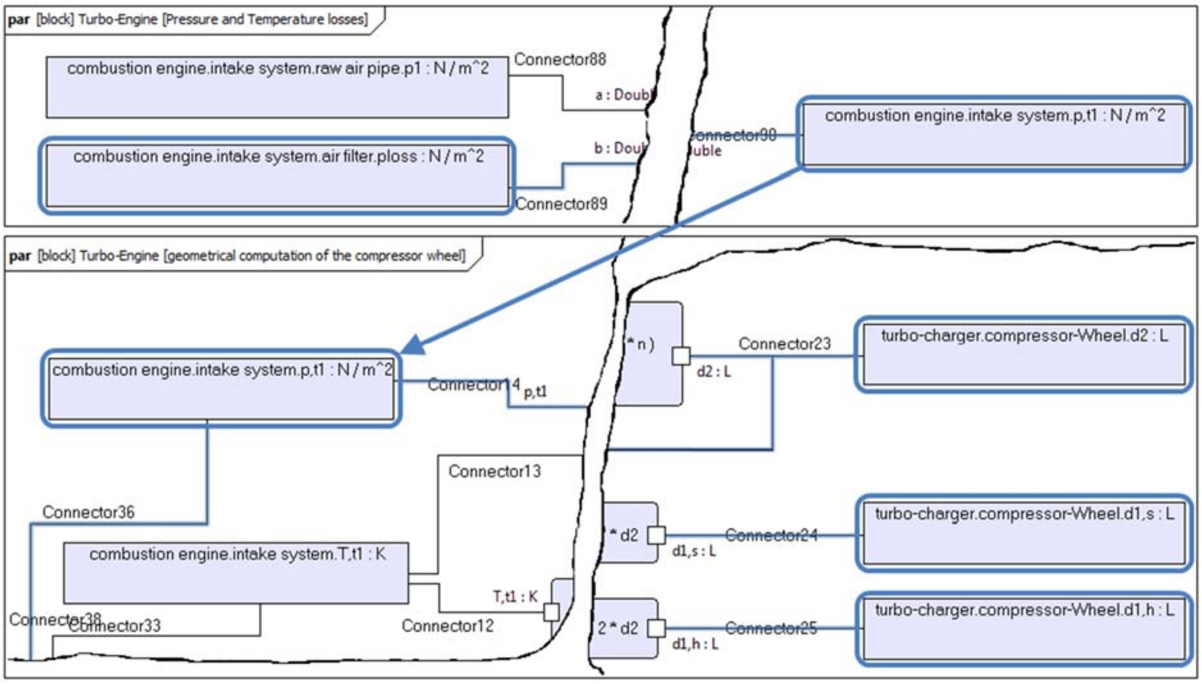

Figure 7. Parametric diagrams affected by the changes to the air filter

Through the modification to the air filter the corresponding properties of the block *air filter* had been affected. These properties are used in one parametric diagram which has the task to compute the total temperature and the total pressure depending on the ambient pressure and temperature. This is carried out by a simple subtraction of the decrease in pressure from the ambient pressure respectively the decrease in temperature from the ambient temperature. Due to the change of the total pressure and temperature it is necessary to have a closer look on this diagram which uses the changed properties. The concerned parametric diagram visualizes the mid-section design of the radial compressor which computes the distinctive dimensions of the compressor wheel. The input parameters for the calculation are the total pressure, the total temperature, the pressure ratio and the air-mass flow. Since two of the four input parameters have changed, modified dimension of the compressor wheel arise. So either the changed dimension can be handed over to an automated calculation of the geometrical shape of the compressor wheel or the respective user is informed that the mid-section design of the radial compressor has to be redone with the new total pressure and temperature.

The changes to the charge air intercooler affect the property representing the outlet temperature which is used in only one parametric diagram. The diagram shows the calculations taking place in the control system to restrict the pressure in the cylinder. The starting point of this calculation is a constraint property which converts the throttle angle desired by the driver of the car into a corresponding set pressure. Besides other input properties, one property represents the outlet temperature of the charge air intercooler required for the calculation of the set pressure. Due to the modification to the charge air intercooler and therefore to the outlet temperature the set pressure is affected. So if the desired throttle angle is identic, another wastegate-angle has to be established in order to get the same boost-pressure. As a consequence, the respective control engineer could be informed of the change in the behavior of the closed-loop control or the change of the outlet temperature could be handed over to the simulation in MATLAB Simulink for purposes of research and development.

4. Conclusion

One promising approach towards interdisciplinary mechatronic design is the application of agent based systems. Prior research showed that such systems need to rely on an interdisciplinary system model and has led to the development of an overall concept for agent based mechatronic design [Stetter et al. 2011]. This paper presents a practical approach in modelling mechatronic systems using the modelling language SysML. During the development of an interdisciplinary development system for turbocharging systems for car engines the main structural, procedural and physical relationships were modelled using three prominent diagrams of SysML. It is observable that SysML is capable of offering the instruments to create a system model of the mechatronic system. Due to the restricted amount of elements used for creating the system model, it is very easy to get familiar with SysML and the creation of system models. But although the amount of elements is restricted, it is possible to build a system model of any thinkable physical system.

The example points out that even before the realization of a full-scale multi-agent system, which is capable to process the system model and to support the participating engineers, the system model has the ability to enhance the design process of mechatronic systems. The reprocessing of the information stored in different documents in an easy understandable and visible way makes domain-spanning information and relationships more clearly. In spite of these immediate benefits, further work is planned to explore the general applicability of the presented approach.

Acknowledgements

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References

Chen, K., Bankston, J., Panchal, J. H., Schaefer, D., „A Framework for the Integrated Design of Mechatronic Systems", In: Collaborative Design and Planning for Digital Manufacturing, Springer London, UK, 2009.

Luck, M., d'Inverno, M., "Understanding Agent Systems", Springer Verlag, Berlin, 2001.

Robert Bosch GmbH, „Dieselmotormanagement. Systeme und Komponenten", Vieweg, Wiesbaden, 2004.

Robert Bosch GmbH, „Kraftfahrtechnisches Taschenbuch", Vieweg+Teubner, Wiesbaden, 2011.

Stetter, R., Seemüller, H., Chami, M., Voos, H., „Interdisciplinary System Model for Agent-Supported Mechatronic Design", Proceesings of the International Conference on Engineering Design'11. Vol. 4, Copenhagen, 2011, pp. 100-111.

Stetter, R., Voos, H., "AGENTES – Agent Based Engineering of Mechatronic Products.",Proceedings of the eight international symposium – TMCE 2010, Mandoril, F., Rusák, Z., (Ed.), Delft University of Technology, Delft, 2010, pp. 855-866.

Trencansky, I., Cervenka, R., „Agent Modeling Language (AML): A Comprehensive Approach to Modeling MAS", Informativa, Vol. 29, No. 4, 2005, pp. 391-400.

Weilkiens, T., „Systems Engineering with SysML/UML – Modeling, Analysis, Design", Morgan Kaufmann Publishers, Burlington USA, 2008.

Weiss, G., "Multiagent systems:a modern appreach to a distrubuted artificial inteligence", The MIT Press, Cambridge/London, 1999.

Prof. Dr.-Ing. Ralf Stetter
Design and Development in Automotive Industry
Department of Mechanical Engineering
Hochschule Ravensburg-Weingarten, Postfach 1261, 88241 Weingarten, Germany
Telephone: ++49(0)751 501 9822
Telefax: ++49(0)751 501 9822,
Email: stetter@hs-weingarten.de
URL: http://www.hs-weingarten.de