Systems Physics Library

Werner Maurer   Elisabeth Dumont

Institut für Angewandte Mathematik und Physik

Zürcher Hochschule für Angewandte Wissenschaften

Technikumstrasse 9, Winterthur, 8401 Switzerland

maur@zhaw.ch   dumo@zhaw.ch

Abstract

In this poster the *Modelica Systems Physics library* is presented. The Systems Physics library is a free open-source library with models for different areas of physics [1]. The primary use of the library is for educational purpose in Physics courses at medium level.

The library contains models from five different domains (hydraulics, translational and rotational mechanics, electrodynamics and thermodynamics). In the future, we plan to add chemistry as a sixth domain. Each domain contains connectors containing a substance-like quantity and the corresponding potential; basic models (capacitance and resistance); sensors and actuators as well as some domain specific elements, such as nonlinear accumulator, nonlinear resistors, valves, springs or inductances. In addition to the constitutive equations each model also comprises the energy balance. For example, dissipative elements calculate the loss energy and even the entropy production with the help of an additional thermodynamic connector.

Keywords: physics; education; system dynamics

1 Introduction

Systems Physics is a novel approach to physics with which beginners are able to grasp the fundamental concepts underlying processes in nature and technology [2]. It is based on everyday concepts known from fluids which are familiar to everybody. The analogy between physical quantities and fluids offers a very intuitive approach to physics [3]. The powerful pictorial modeling offered by Modelica helps students to understand basic physical processes.

Moreover, here is an immense number of problems that can be addressed by this approach which are usually not included in the standard physics textbooks at undergraduate level. With the help of this Modelica library, students are able to model rather complicated physical systems (e.g. friction) with little mathematical knowledge.

In the first two semesters at the ZHAW School of Engineering students learn the modeling concept of system dynamics with Stella or Berkeley Madonna. Thereby they learn the basic structures and formulas (balance equation, constitutive laws and the energy carrier concept) of physics. The *Systems Physics* library could then be used in subsequent semesters in order to deepen this knowledge.

Systems Physics combines the modeling concept of System Dynamics with a unified description for all branches of classical physics known from Bond Graph theory [4]. Our concept of energy carrier is similar to that of the Bond Graph theory. But there is a crucial difference. In Bond Graph theory, force and torque are potential quantities (effort quantities) and the kinematic variables velocity and angular velocity are seen as flow quantities. In Systems Physics however, this approach is not possible because force and torque are part of the balance equation and velocity and angular velocity are the "driving force" for the appropriate currents. Therefore force and torque are flow variables and the two velocities are effort or potential quantities.

In our model based approach students start by formulating the balance of a fundamental quantity (bathtub-thinking for volume, mass, electrical charge, momentum, angular momentum, entropy or amount of substance). Then they have to specify the currents and the rates of change (feedback-thinking). On a second layer they can add the balance of energy (bookkeeper-thinking).

Our vision of a new physics course for engineers or natural and medical scientists covers system dynamics modeling in the first year and object-oriented modeling in the following years of studies [5].

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2 Structure

The systems physics library includes the domains hydraulics, electrodynamics, translational mechanics, rotational mechanics, thermodynamics and chemistry. Each domain includes a substance like quantity and a corresponding potential. All connectors are constructed according to this basic structure (Table 1)

In all branches of physics there are many different storage systems such as tanks, plastic bottles, capacitors, moving or rotating bodies, heat accumulators. For each storage system we can write down two balance equations: one for the basic quantity M (volume, electric charge, momentum, angular momentum, entropy); and one for the Energy W. The balance equations for M and W are given by

$$\sum_i I_{M_i} = \frac{dM}{dt} \tag{1}$$

$$\sum_i I_{W_i} = \frac{dW}{dt} \tag{2}$$

where I_M are substance currents and I_W are energy currents. For the entropy balance equation a production rate Π_S is introduced in addition to entropy currents.

The domain specific potential φ_M (pressure, voltage, velocity, angular velocity and absolute temperature) connects the current for the basic quantity with the energy flux

$$I_W = \varphi_M I_M \tag{3}$$

A Model with two ports and a conserved quantity (ideal volume, electric charge, momentum or angular momentum) contains at least one equation for conservation and one for the power

$$I_{M1} + I_{M2} = 0 \tag{4}$$

$$P = \Delta\varphi_M I_M \tag{5}$$

These equations are formulated in separate *partial models*. In thermodynamics we need two different partial models, one for heat conductance which conserves energy

$$T_1 I_{S1} + T_2 I_{S2} = 0 \tag{6}$$

and one for ideal heat engines which conserve entropy

$$I_{S1} + I_{S2} = 0 \tag{7}$$

An additional equation calculate the production of entropy in the partial model for heat conductance

$$I_{S1} + I_{S2} = \Pi_S \tag{8}$$

or the power in a partial model for ideal heat engines

$$P = \Delta T I_{S1} \tag{9}$$

Ideal heat pumps are modeled similar to hydraulic pumps: in the same way as a hydraulic pump pumps water or oil heat pumps pump entropy. This is one of the main messages of Systems Physics.

Table 1: flow and potential variables in the different domains of Systems Physics

domain	quantity	potential
hydraulics	volume	pressure
electrodynamics	charge	voltage
translational mechanics	momentum	velocity
rotational mechanics	angular momentum	angular velocity
thermodynamics	entropy	temperature

2.1 Hydraulics

The volume of an incompressible fluid is the basic quantity in hydraulics and pressure is the associated potential. Because pressure multiplied by volume flow equals the flux of energy, the conservation of energy is guaranteed.

The hydraulics library includes different storage elements like open vessels, spring-loaded tanks and other accumulators, pipes with laminar and turbulent flow characteristics as well as various valves. The inertia of the fluid flowing through the pipe is responsible for the inductive effect. In all three system categories (capacitance, resistance and inductance) the stored or dissipated energy is calculated. In an additional resistor element, the entropy is recalculated and is connected by a thermal connector. The temperature of this connector determines the viscosity of the fluid.

Two ideal pumps are modeled, one with a signal input for pressure difference and one with a signal input for the volume flow rate. In addition, the library contains sensors for pressure and volume flow.

2.2 Electrodynamics

The electrodynamics library based on the Modelica standard libraries with capacitor, resistor, diode and inductor. In addition, an isolated metal sphere is modeled for charge storage in experiments with high voltage.

The energy balance is calculated in all elements. This calculation is made for didactic purpose and for energy check in complex systems. A resistor with a thermal connector wherein the entropy is calculated enables the modeling of electro-thermal elements such as resistance heating or light bulb.

2.3   Mechanics

The mechanics library includes two parts: one for motion along a straight line and one for rotation around a fixed axis. Therefore, the associated quantities momentum and angular momentum can be treated as scalars. The similar statement is true for the associated potentials (velocity and the angular velocity). The tight separation of the balance equation for momentum or angular momentum from kinematics has some implication: mass and moment of inertia have only one connector and distance or angle can only be calculated in elements that describe the flow of momentum or angular momentum.

In addition to the linear systems some more elements, such as friction, air resistance or elastomer spring are modeled. An ordinary rope or string is a further element often used in physics instruction. It is modeled as a spring-damper-system with predetermined breaking point. As in hydraulics and electrodynamics some elements for momentum or angular momentum flow are provided with a heat connector. The produced entropy is calculated and the temperature has an influence on the constitutive laws of these elements.
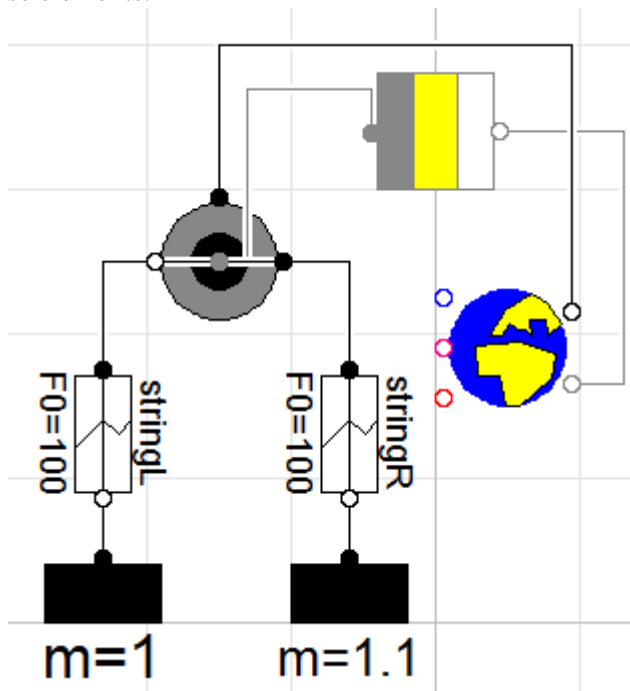

Figure 1: A model of an Atwood machine with two weights and bearing friction. The symbolic earth with five connectors for the flow of volume, momentum, angular momentum, electric charge and entropy stands for the surrounding.

The mass element has a momentum source which strength corresponds to the tangential component of the weight force. A further element contains the equation for the relativistic mass. In this element,

energy and momentum are connected with the help of the famous Einstein equation. The model of a simple rocket engine completes the model zoo, although this element belongs to the open systems, which are not included in this library. Figure 2 shows the velocity-time behavior of a rocket another system that can be easy modeled with our approach.
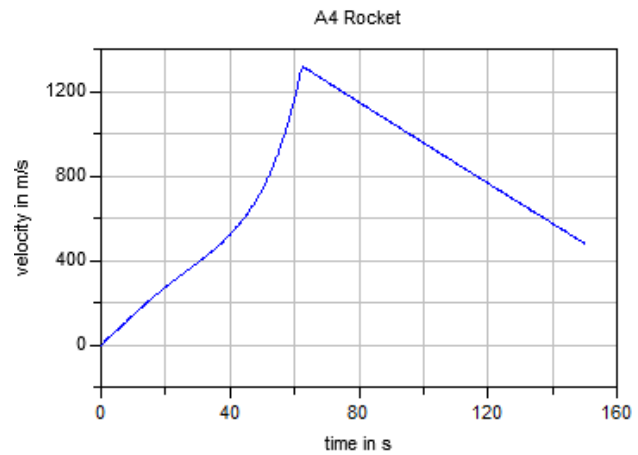

Figure 2: Velocity-time-diagram of a rocket ascending in an isentropic atmosphere with constant gravitational field

Translational and rotational mechanics are connected to each other by means of pulleys. The corresponding model has four connectors, three for translation and one for rotation. With two bodies, two strings, a pulley and a bearing friction, we can model Atwood's machine (Figure 1).

2.4   Thermodynamics

If we take entropy as the basic quantity of thermodynamics it's easier to write down the correct equations than if we take the energy as a conserved quantity [6]. However, for the equations themselves, it does not matter whether we start from the energy or from entropy as we have shown in the introduction. There are two different models which specify the transport of heat, the heat conduction and the ideal heat engine.

We describe homogeneous systems, which are heated at a constant pressure, with the state variable enthalpy H. Enthalpy is a special form of energy and a thermodynamic potential. Although entropy flow and temperature are calculated in the connector, this is no problem with respect to the balance equation for energy

$$TI_S = \frac{dH}{dt} \qquad (10)$$

More generally, a homogeneous thermodynamic system can at least change entropy and volume. Therefore the system has temperature and pressure as two associated potentials. To discuss and model

such a system we have developed the Carnotor, a simple machine with a thermal and a hydraulic connector (Figure 3). Carnotor is a portmanteau composed of Carnot and Motor (German word for engine).

The Carnotor consists of a double-acting cylinder filled with the substance to be examined on one side of the piston and an ideal fluid on the other side. To each port we can add a pump, a closing-off or a big storage tank. With this equipment students can analyse all four basic processes of thermodynamics (Table 2).

The corresponding model calculates pressure and temperature from the change of volume and entropy. For the ideal Gas, the constitutive laws are as follows

$$S = S_0 + nR \ln\left(\frac{V}{V_0}\right) + \frac{f}{2} nR \ln\left(\frac{T}{T_0}\right); \qquad (11)$$

$$pV = nRT \qquad (12)$$

f stands for the degrees of freedom of gas molecules , n for the amount of substance and R for the gas constant. Equation (12) is known as ideal gas low.

Table 2: The four basic processes in thermodynamics

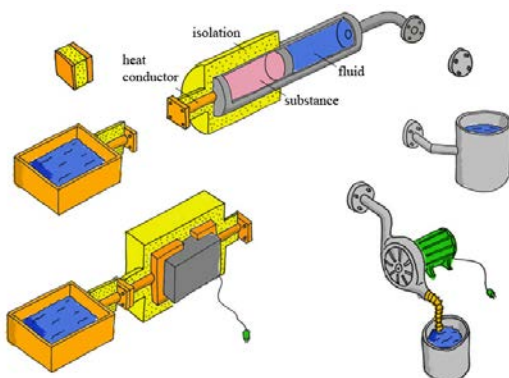| process	heat port	hydraulic port	unchanged
isochoric	heat pump	closing-off	volume
isobar	heat pump	storage tank	pressure
isentropic	closing-off	hydraulic pump	entropy
isotherm	storage tank	hydraulic pump	temperature

Figure 3: The Carnotor has two ports, one for heat and one for an ideal fluid. Both ports can be combined with a closing-off, a storage tank or a pump
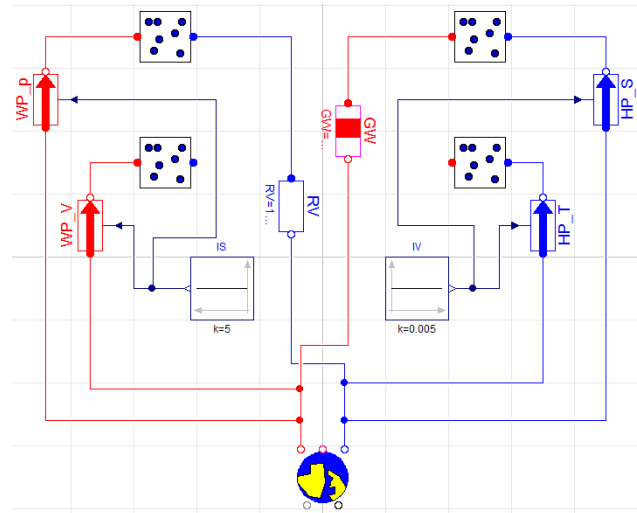

Figure 4: This system contains four models for ideal gas, two ideal heat pumps, two ideal hydraulic pumps, a heat flow and a volume flow element.

The Carnotor can be taken as the core element for a lot of thermodynamics engines. Figure 4 shows a model with which one can simulate all four basic processes simultaneously

3 Conclusions

Systems Physics provides a consistent, coherent and relevant structure of physics. A huge number of dynamical systems can be modeled with the same heuristic approach. The equation of balance for substance-like quantities like volume, mass, electric charge, momentum, angular momentum and entropy yields the backbone for such models. By adding the constitutive laws for accumulators and conductors we get the basic equations. In a third step we can add energy as a second substance-like quantity. The energy balance analysis is often useful but not necessary for simple systems. But energy conservation becomes an inevitable requirement in more complex systems like thermodynamic accumulators.

Systems Physics has been developed on the basis of the Karlsruher Physikkurs [7] and taught in different physics courses at Zurich University of Applied Sciences.

With the help of the *Systems Physics library* we hope that we can convince more and more teachers of the usefulness of this method. A countless number of dynamic models are waiting to be modeled with a System Dynamics or a Modelica tool.

On Youtube you can find some tutorials on specific topics of the *Systems Physics library* [8]

References

[1]   http://code.google.com/p/system-physics/

[2]   Borer, T et al.(2010). Physik – Ein system-dynamischer Zugang für die Sekundarstufe II. hep, Bern.

[3]   Maurer, W (2002). Systemdynamik – Ein möglicher Pfad durch den Irrgarten von Fehlvorstellungen. PdN-PhiS. 7/51, Aulis, München.

[4]   Karnopp, D., Margolis, D., Rosenberg, R. (1990). System dynamics: a unified approach. Wiley, New York.

[5]   Maurer W. Physik und Systemwissenschaft in Aviatik. Proceedings of the 20th Symposium on Simulationtechnique ASIM 2009, Cottbus,Germany, ASIM September 23-25, 2009.

[6]   Fuchs H (2010). The dynamics of heat. Springer, New York.

[7]   2005.Friedrich Herrmann et al. (2010): Der Karlsruher Physikkurs. Aulis, München.

[8]   http://www.youtube.com/user/Systemdynamiker (playlists *Modelica-Kurs* and *Modelica*).