

# Electromagnetic actuator modeling for modular robotics applications

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The paper presents the modeling stage of an electromagnetic actuator, used for connecting/disconnecting modular robots. An impedance based graph method was used, pointing out the energy storing feature of magnetic core, unlike the dissipative character of reluctances method.

(Received March 13, 2008; accepted May 5, 2008)

*Keywords:* Robotics, Electromagnetic actuator, Modeling

## 1. Introduction

Modular robots with self-reconfiguring skills, even closed to the science fiction now, will be a fundamental technology of the future. A system consisting of a set of standard mechatronic modules, which can connect or detach automatically, can provide a great versatility of use, robustness, low cost and the self-repairing, by ease of modules replacement. It can be re-assembled in a large variety of configurations, adapted to the ground, environment and task. Some possible configurations of the first version of the robot ROMAR are presented in fig.1.

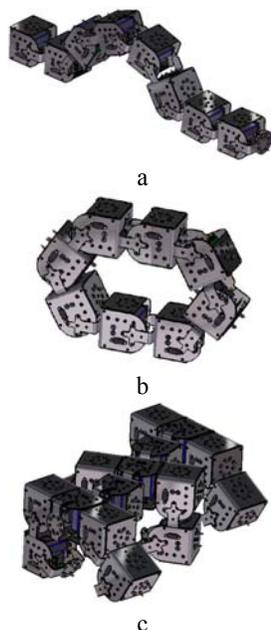


Fig. 1. Modular robot configurations: a) chain with caterpillar motion; b) wheel; c) intermediate stage during re-configuration.

The connecting/disconnecting mechanism could make use of permanent magnets, solenoids, shape memory alloys actuators springs and adequately shaped parts, which perform a version of the peg-in-a-hole problem. For the module of the robot ROMAR, it was conceived a mechanism consisting of several crosses (one for each connecting face of the modular cube) locking the male pins which are located on the adjacent module (fig.2, a). This is actuated by an electromagnet (fig.2, b) and a helical spring (fig.2, c).

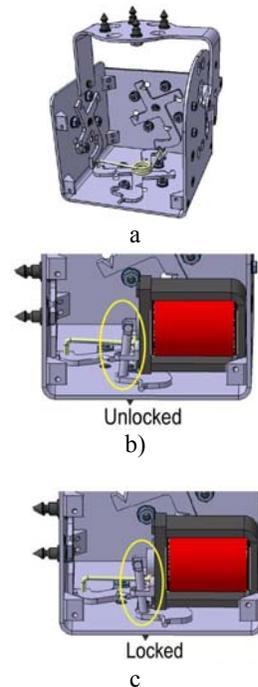


Fig. 2. Connecting/disconnecting mechanism: a) spatial locking mechanism; b) electromagnetic actuator in unlocked position; c) electromagnetic actuator in locked position

This is a mechatronic system which requires modeling and simulation during all the development stages, from conceptual design to manufacturing. A very accessible way to model physical systems is to use intuitive graph methods.

Even based on the same equations, describing the physical phenomena and the constraints of the system interaction with the environment, the graph methods represent systematic approach which facilitates mechatronic systems modeling. By example, linear graphs, equivalent to impedance diagrams of mechatronic systems, could be built by use of reversed electro-mechanical analogy [1], [2]. This kind of modeling is assisted by some programming environments, such as SPICE, SPICE-like simulator for MATLAB or PSIM, a.s.o. They can be very useful for mechatronic modeling, with the adequate coupling between domains, especially when modeling sensors and actuators.

Another graphical approach to mechatronic system modeling is known as bond graph analysis, which is the representation of energetic interactions between components as oriented lines standing for power bonds [3]. Similar to electric networks, there are simulation languages, based on bond graphs representation of physical systems such as SYMBOLS 2000 or 20-sim.

## 2. Generalized variables and elements

Modeling and simulation of the dynamic behavior of a mechatronic system has as final goal to obtain its description in mathematical form and, then to solve the equations for achieving the system response for certain inputs.

As an inter- or trans-disciplinary engineering science, mechatronics deals with different physical domains, for which different variables are defined: voltage and current in electrical systems, force and velocity in mechanical ones, pressure and flow rate in fluid systems, etc.

Based on fundamental similarities of mathematical description and related to energy manipulation, an unified way to represent systems and components was derived, as well a pair of generalized variables was defined. It takes into consideration the energetic interactions between system elements via so-called ports (power connection), by means of system variables, whose product evaluates the transmitted power. For an abstract energy port, an intensive variable, giving the flux of energy flow (current, fluid flow rate) is called *flow* variable and an extensive variable showing the potential of energy flow (voltage, pressure) is called *effort* variable. Sometimes, these variables are also called *through* and *across* variables, due to the required connection for their measuring [4]. This form is basically adequate for network representation of systems, when generalized impedances are used. When physical causality is taken into consideration, the variables from the mechanical field have to change their significance in terms of *effort* and *flow*, thus the force becoming an effort and velocity a flow. It is the case of *bond graph* representation. The variables from other

physical domains keep their significance (voltage, pressure -effort and current, flow rate – flow).

## 3. Network method

Mechatronic systems modeling should be initiated by defining the system boundary and its dividing into basic components. This is the regular case of system representing by lumped parameters. Another important class of elements is the sources of *effort* and *flow*, both constant and modulated or controlled. For the electrical field it is common to build networks as circuits or linear graphs, but for the mechanical one it is necessary to identify the points with different velocities (*effort variables*), in order to define the nodes (vertices) of the graph. The line segments which interconnect the nodes (edges) also characterize the power flow, representing the *flow variable*, derived from constitutive equations of the elements. It is advantage to express all these constitutive equations in terms of generalized impedance  $Z(s) = e(s)/f(s)$ , because a block diagram for MATLAB/ Simulink can be easily derived, by applying Kirchhof's laws. This is based on the typical electric circuit representation, for which the element is connected in nodes, characterized by across variable (fig.3). In mechanical systems, inertial elements have their velocity measured against the reference frame (ground), so such an element should be connected in a network between the vertex with its velocity and the ground. The other elements have always a relative velocity between their ends.

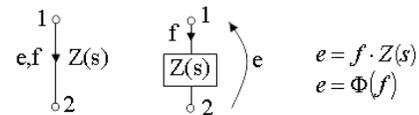
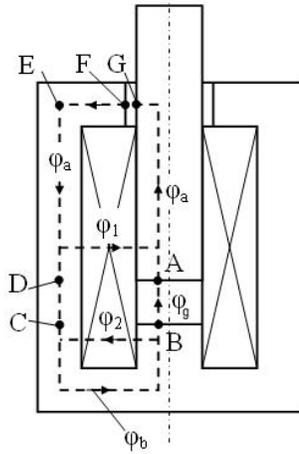


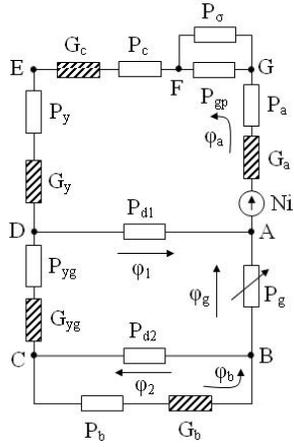
Fig.3. Linear graph representation of a basic element.

The electromagnetic actuator is particularly interesting when modeling the magnetic circuit. Usually, the physical model is represented in terms of reluctances or permeances of the magnetic core. This is due to the regular analogy, which makes the well known correspondence *magnetic flux-current* and *magnetomotive force-voltage*. The result is that the reluctance seems to have a dissipative character, while it is known the device is storing the energy. Another approach is proposed in [3], by taking as magnetic *through variable* the derivative of the flux linkage,  $\lambda = N \phi$ . The magnetomotive force, which tends to set up the magnetic flux  $\phi$  in the yoke is related to the current through the coil by  $M = N \cdot i$ . In the same time, for a part of the magnetic core or air gap, the magnetomotive force drop is:  $M = \phi / P = \dot{\phi} / (Ps)$ , where  $P$  is the permeance (inverse of the reluctance). This equation shows an analogy between permeance and inertial mass or capacity from mechanical and electric domains, respectively. When evaluating reluctances or permeances, Rotters's method of volumes is used and it results generally as  $P = \mu A / l$ , where:  $\mu$

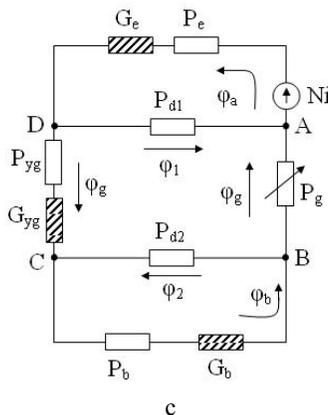
- magnetic permeability;  $A$  – cross section area;  $l$  – length. All the parameters refer to the core section or air gap.



a



b



c

Fig. 4. Magnetic circuit and permeance network: a) magnetic core; b) permeance network model; c) simplified model

The magnetic permeances of the actuator core, moving armature and air gap, P are shown in fig.4, together with resistive components, G, which take into

consideration the influence of eddy currents upon the magnetic flux variation and losses. This model was developed by Schweer [5] and simply express the magnetomotive force between 2 points of the magnetic path (fig.5) as:

$$M = \varphi / P_y + G_y \dot{\varphi} \quad (1)$$

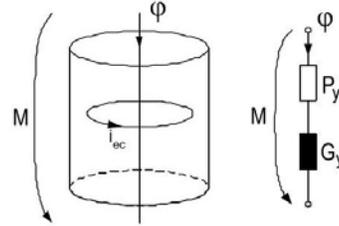


Fig. 5. Magnetomotive force modeling on a part of the magnetic path.

where  $P_y$  is the core permeance and  $G_y$  – iron conductance of the eddy current path.

The principles of building the device graph, described above, are applied for the electromagnetic actuator and the result is presented in fig.6. From it, the following equations can be derived:

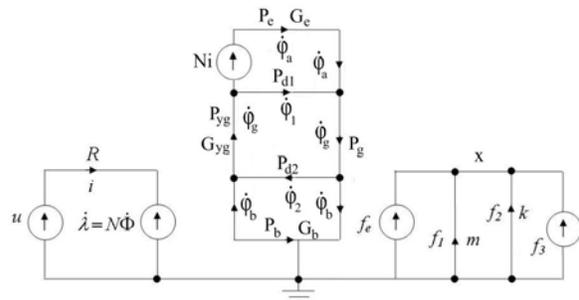


Fig. 6. Linear graph of the actuator and actuated mechanism

$$u = u_R + e; \quad u_R = Z_R \cdot i; \quad e = N \cdot \dot{\varphi}; \quad Z_R = R; \quad \text{- electric network} \quad (2)$$

$$\begin{aligned} N \cdot i &= \varphi_a / P_e + G_e \dot{\varphi} + \varphi_1 / P_{d1}; \\ \varphi_1 / P_{d1} + \varphi_2 / P_{d2} &= \varphi_g / P_g + \varphi_g / P_{yg} + G_{yg} \dot{\varphi}_g; \\ \varphi_2 / P_{d2} + \varphi_b / P_b + G_b \dot{\varphi}_b &= 0; \quad \varphi_a = \varphi_g + \varphi_1; \quad \varphi_b = \varphi_g + \varphi_2 \end{aligned} \quad \text{- magnetic network} \quad (3)$$

$$f_e = \varphi_g^2 / (2\mu_0 A) = f_1 + f_2 + f_3 \quad \text{- magnetic - mechanical coupling} \quad (4)$$

$$x = f_1 / (m \cdot s^2); \quad f_2 = k \cdot x; \quad f_3 = F_0 \quad \text{- mechanical network} \quad (5)$$

The significance of variables and parameters are denoted from fig. 4 and 6.  $F_0$  takes into consideration the preload of the spring and friction in mechanism.

The nonlinear character of the magnetic phenomena can be modeled by assuming a simple B-H magnetization curve according to Froelich:

$$B = C_1 H / (C_2 + H) \quad (6)$$

Froelich constants  $C_1$  and  $C_2$  are the values of the saturation magnetic flux density and, respectively, the magnetic field strength in the point of maximum

permeability. By use of (6), the permeance of a part of the core can be expressed as:

$$P_y = (C_1 A - \varphi) / (C_2 l) \quad (7)$$

where  $A$  is the cross section area and  $l$  – length of the magnetic path.

The equations (2) - (5), and (7) can be simply transformed into a block diagram (Simulink, by example) by only taking into consideration to avoid derivative causality, due to the calculation errors. The result is presented in fig.7 and it is valid for the assumption the actuator works both on the linear and nonlinear region of the magnetization curve, B – H.

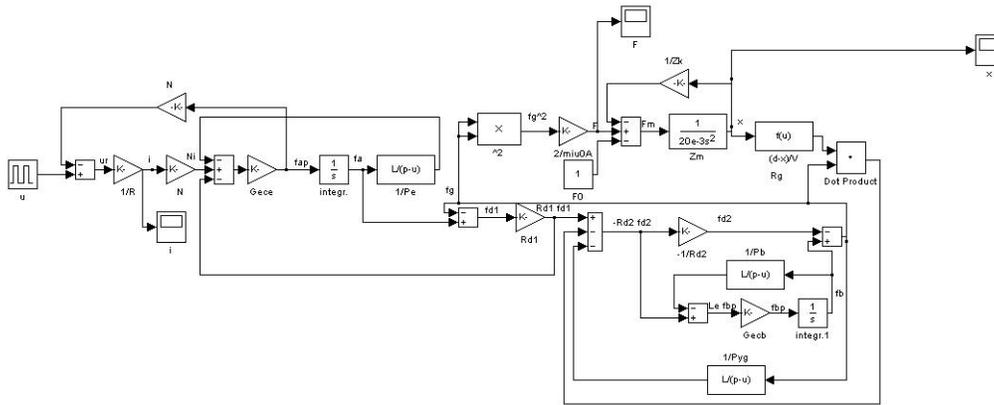


Fig. 7. Block diagram of the graph in fig. 6.

**4. Bond Graph method**

Bond Graphs represent the energy flows in mechatronic systems and also handle generalized power-variables: effort  $e$  and flow  $f$ , as well momentum  $p$  (integral of effort) and displacement  $q$  (integral of flow). The energy flow between different subsystems is represented by a ‘bond’ looking like a half arrow. An example of a word bond graph of the system from fig.6 is shown in fig.8.



Fig.8. Word bond graph of the electromagnetic actuator.

junctions (common flow, as in a series electric circuit), transformers (TF) and gyrators (GY). These junctions are considered as being power conservative. A 0-junction and a 1-junction are shown in fig.9.

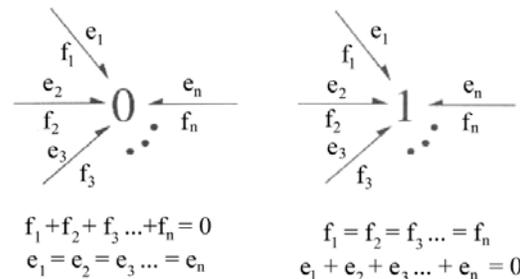


Fig.9. 0-junction and 1-junction rules

In a lumped parameter model, each subsystem consists of basic elements, which can be classified in passive and active elements. There are 3 types of passive elements, defined from the electromechanical analogy, but taking the force (torque) in the mechanical domain as *effort* variable and velocity (angular velocity) for *flow* variable. Active elements are sources of effort  $Se$  and sources of flow  $Sf$ . If their output is controlled by a signal, they are called “modulated”. Elements can be connected with 0-junctions (common effort, as in a node of an electric circuit), 1-

A very important property of bond graphs in system representation is related to causality. It is graphically defined by a small stroke perpendicular to bond arrow, placed at one end. This indicates the cause-effect relationship, between 2 elements, as it is shown in fig 10, for a resistive element.

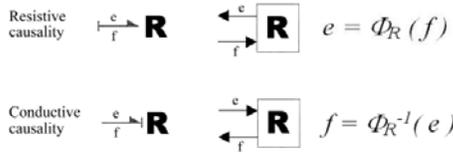


Fig.10 Causality assignment.

The electromagnetic actuator, modeled by linear graph method can be also modeled by help of the bond graphs method. The actuator bond graph, as it is systematically built by identifying basic elements is presented in fig.11. It can be simplified according to the rules from [3], [4], as well automatically by means of the used software (20-sim). The result is shown in fig.12. In both diagrams (fig. 11 and 12), a gyrator is used for relating the voltage and current in the coil to the rate of flux change and magnetomotive force. Another specific element for coupling between magnetic and mechanical domains is the 2 port C-field, which relates magnetic flux and electromagnetic force.

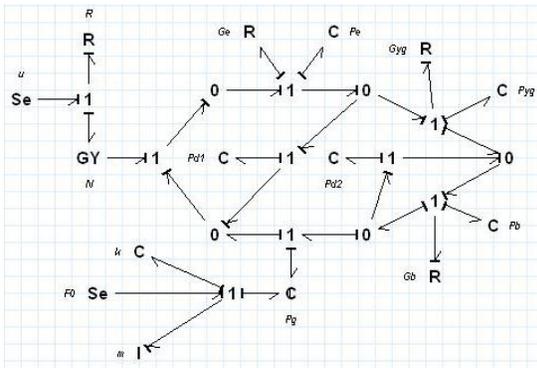


Fig.11. Bond graph of the actuator and actuated mechanism.

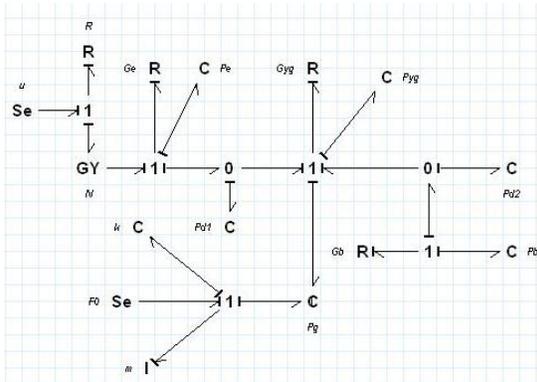


Fig.12. Simplified bond graph.

There are methods for transforming the bond graph representations into block diagrams, as well systematic procedures for deriving the system equations. Anyway,

some programming environments have the possibility to process directly the data from the graph [6].

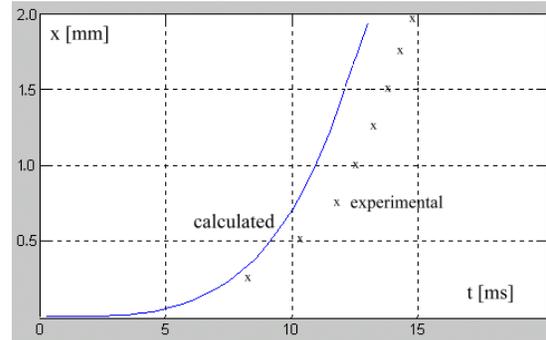


Fig. 13. Simulation results.

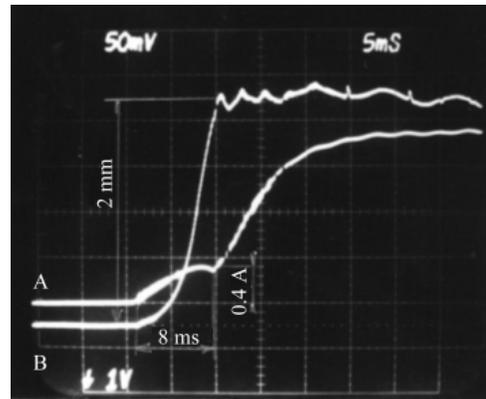


Fig. 14. Measured data.

In fig.13, it is presented the simulation results for the electromagnetic actuator developed for unlocking the connection between two robot modules, having the parameters:  $m = 18 \times 10^{-3}$  kg;  $k = 93$  N/m;  $A = 39 \times 10^{-6}$  m<sup>2</sup>;  $N = 551$ ;  $R = 7.8 \Omega$ ;  $u = 9$  V;  $C_1 = 1.9$  T;  $C_2 = 431$  A/m.

### 5. Conclusion

Electromagnetic actuators are typical mechatronic systems because they encounter three physical domains which have to be simultaneously analysed during design stage: electric, magnetic and mechanical. This is a mechatronic approach indeed and design methods and tools are under current development. Among these, graph methods are powerful and easy to use tools for modeling and simulation of the dynamic behavior of the mechatronic systems. Besides traditional modeling by block diagrams, there are more sophisticated object-oriented programming environments, based on the mathematical model of components and providing the possibility to directly implement these methods into the applications. For the

considered application, both network method and graph bond one were applied with satisfying results.

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