MODELING AND SIMULATION OF MECHATRONIC SYSTEM TO INTEGRATED DESIGN OF SUPERVISION : USING A BOND GRAPH APPROACH

Mohamed Arezki Mellal
Solid Mechanics and Systems Laboratory
M'Hamed Bougara University
Boumerdès, Algeria
E-mail: mellal-mohamed@umbb.dz

Smaïl Adjerid
M'Hamed Bougara University
Boumerdès, Algeria

Djamel Benazzouz
M'Hamed Bougara University
Boumerdès, Algeria

KEYWORDS
Modeling, Simulation, Mechatronic system, Bond graph approach, Integrated design of supervision.

ABSTRACT

The research in mechatronics focuses on the design and implementation of reliable, secure and economic systems. Our study is to modeling the operative part of a CNC machine using a bond graph approach with optimal placement of sensors in order to achieve a model for an integrated design of supervision. The proposed model allows a conception technically feasible and economically realizable to be integrated into production lines. The generation of analytical redundancy relations can find the FDI (Fault Detection and Isolation) matrix, that optimizes the maintenance function.

INTRODUCTION

Mechatronics is the synergistic and systemic combination of mechanics, electronics and computers in real time, the value of this pluridisciplinary engineering field is to design powerful, reliable, economic and automated systems to allow control of complex systems (Bishop 2006). From this definition we deduce that each mechatronic system can be modeled and simulated with an efficient in the design phase.

A unified modeling approach is necessary for analysis and mode. The graphical tool is well suited for this purpose. This methodology allows the display of the power exchange system, which includes storage, dissipation and transformation. In addition, this tool takes into account not only the generation of a behavior of the system, but it can also be used for structural and causal analysis, which is essential for designing control systems and surveillability. The flexibility of this tool allows us to add more elements such as losses or thermal effects. The causal and structural properties of the graphic language allows the modeler to solve the algorithmic level model in the formulation stage before the detailed equations have been derived, this context has been developed in (Samantaray and Ould Bouamama 2008).

These properties can be used for the design of systems for monitoring and supervision, these methods are illustrated in (Ould Bouamama 2002; Djeziri et Ou. 2009; Medjaher et Sa. 2006; Cocquempot 2004). Therefore, this graphical method can be considered an integrated tool for computer-aided design. The bond graph, abbreviated by (BG) are, (Ould Bouamama and Tanguy 2006) :

- Representation graphs of the dynamic behavior of systems regardless of the domain considered.
- Graphs based on energy flow.
- An object-oriented modeling of systems.
- A powerful modeling tool for engineers.

In the bond graph language there is a set of multiports which are necessary for modeling a physical system in a generic way using generalized variables of effort and flow. These elements are classified into three categories, (Ould Bouamama and Tanguy 2006): three passive elements (R, C and I), two active elements (Se and Sf) and four junctions (1, 0, TF and GY). The notion of causality has been developed in (Borutzky 2009).

CASE STUDY

In our study we model and simulate the operative part of a CNC machine using the bond graph tool to lead a model for integrated design of supervision. This machine consists of two parts:

- Control part for machining program, instrumentation and monitoring display.
- Operative part for piece machining.

An electric motor drives through: set reductor and screw/nut, a table piece porter moving horizontally. The engine is powered by a voltage V_{in} and the table is marked with its rated position Pos(t), view figure 1.

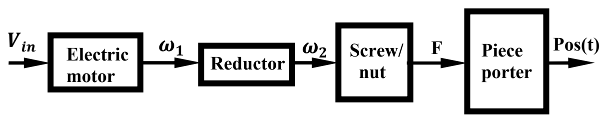

Figure 1: Presentation of the table.

The parameters of the table are illustrated in the table 1, (Vergé and Jaume 2004):

Proceedings 25th European Conference on Modelling and Simulation ©ECMS Tadeusz Burczynski, Joanna Kolodziej Aleksander Byrski, Marco Carvalho (Editors)
ISBN: 978-0-9564944-2-9 / ISBN: 978-0-9564944-3-6 (CD)

Table 1: Parameters of the table.

Value	Definition	Unit
Kv = 0,47	Constant of the motor	(rad/s)/v
L = 0,0019	Inductance of the motor	H
R = 0,61	Resistance of the armature	Ω
J = 0,01	Inertia of the rotating part	kg·m²
n = 0,5	Reduction ratio	
h = 0,01	Pitch of the screw	m/rad
M = 8	Mass of the table	Kg
f = 6000	Viscous friction	N·s/m
k = 300000	Stiffness	N·m/rad

MODELING AND SIMULATION OF THE BOND GRAPH MODEL

Modeling is to build the bond graph model into the software. In our case we have chosen the SYMBOLS 2000 (The BondPad module), that is powerful for research. A comparative study of different software has been treated in (Djeziri 2007; Mellal 2009). The figure 2 shows the bond graph model proposed which was modeled on SYMBOLS 2000:

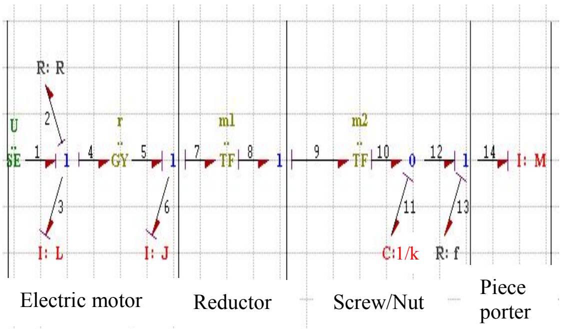

Figure 2: Bond graph model proposed.

This bond graph model has allowed us to ask analytically all equations of the system without reducing the causal path:

Junction 1 : I

$$\begin{cases} f_1 = f_3 = f_4 = \{f_2\} \\ e_2 = V_2 - e_3 - e_4 \end{cases} \quad (1)$$

Element I : M

$$\begin{cases} \dot{p}_{12} = e_{12} \\ f_{12} = \frac{1}{M} \times p_{12} \end{cases} \quad (2)$$

Junction 1 : ω_1

$$\begin{cases} f_5 = f_7 = \{f_6\} \\ e_6 = e_5 - e_7 \end{cases} \quad (3)$$

Element C : 1/k

$$\begin{cases} \dot{q}_9 = f_9 \\ e_9 = k \times q_9 \end{cases} \quad (4)$$

Junction 0

$$\begin{cases} e_8 = e_{10} = \{e_9\} \\ f_9 = f_8 - f_{10} \end{cases} \quad (5)$$

Element R : R

$$e_3 = R \times f_3 \quad (6)$$

Junction 1 : Motor

$$\begin{cases} f_{11} = f_{13} = \{f_{12}\} \\ e_{12} = e_{11} - e_{13} \end{cases} \quad (7)$$

Element R : f

$$e_{13} = f \times f_{13} \quad (8)$$

Element I :L

$$\begin{cases} \dot{p}_2 = e_2 \\ f_2 = \frac{1}{L} \times p_2 \end{cases} \quad (9)$$

Transformer TF : m_1

$$\begin{cases} f_8 = m_1 \times f_7 \\ e_7 = m_1 \times e_8 \end{cases} \quad (10)$$

Element I : J

$$\begin{cases} \dot{p}_6 = p_6 \\ f_6 = \frac{1}{J} \times p_6 \end{cases} \quad (11)$$

Transformer TF : m_2

$$\begin{cases} e_{11} = \frac{1}{m_2} \times e_2 \\ f_6 = \frac{1}{L} \times p_2 \end{cases} \quad (12)$$

Gyrator GY : r

$$\begin{cases} e_5 = r \times f_4 \\ e_4 = r \times f_5 \end{cases} \quad (13)$$

The SYMBOLS 2000 allows directly generate the simplified equations. It takes into account the causal and causal paths, hence the elimination of unknown variables. The rank of the proposed bond graph model is four (I:L ; I:J ; C:1/k ; I :M) and we obtained the same number of equations (view figure 3), this confirms that our bond graph model is well structured (causality, coupling and information links).

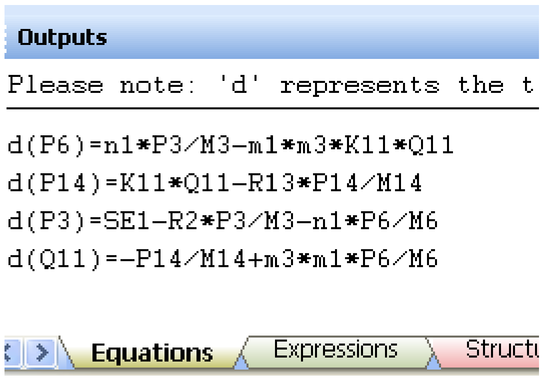

Figure 3: Equations generated by the software.

CONSTRUCTION OF CAPSULES TO GENERATE THE FDI MARTRIX

This software can also make out the fault detection and isolation matrix, to model a system of oversight on this program we must construct capsules that contain the various components of the system, therefore a capsule is the bond graph of each part of the system that assigns a representative icon. These capsules are connected with sensors that are coupled to junctions. In SYMBOLS 2000 we have only capsules of process engineering, hence the need to build our own capsule to our system.

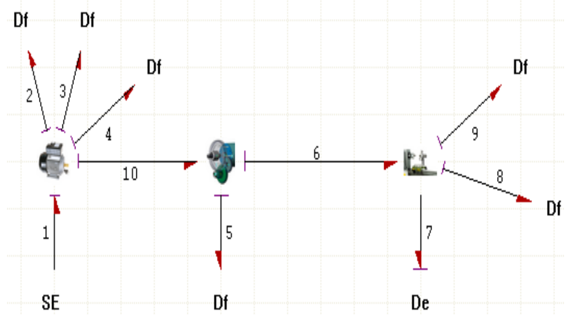

Figure 4: System modeled by the built capsules.

Df_2 : Detector of the motor's internal resistance.
Df_3 : Detector of the motor's inductance.
Df_4 : Speed detector of the motor's rotating part.
Df_5 : Speed detector of the reductor.
De_7 : Torque detector.
Df_8 : Speed detector of the set screw/nut.
Df_9 : Speed detector of piece porter.

RESULTS

The BG model allows to obtain the numerical values of the residues but also the matrix of failure signature S_{ij}. Indeed, this later is essential for localization of failures may occur during operation of the system. The route of the causal paths helps to eliminate the unknowns variables to generate the RRAs (Analytical Redundancy Relations). The route of the causal paths of unknown variable to the sensor is used to construct the matrix of failure signature, the figure 5 show the RRAs generated.

```
Arr1=Moteur_m1*Df2_Measurement-Réduct_m2*(VisEcrou_m2*De1_Measurement
     +Réduct_I4*ddt(Réduct_m2*Df3_Measurement))
Arr2=Df6_Measurement-(De1_Measurement-VisEcrou_I6*ddt(Df6_Measurement))/f
Arr3=Df2_Measurement-(U_Input-Moteur_I3*ddt(Df2_Measurement)
     -Moteur_m1*Df3_Measurement)/R
Arr4=VisEcrou_m2*Réduct_m2*Df3_Measurement-VisEcrou_C4*ddt(De1_Measurement)
     -Df6_Measurement
Arr5=Réduct_m2*Df3_Measurement-Df4_Measurement
Arr6=Réduct_m2*Df3_Measurement-Df5_Measurement
Arr7=Df2_Measurement-Df1_Measurement

s  Expressions  Structural  FDI
```

Figure 5: RRAs generated by the software.

DISCUSSION

From these results, we note that :

- Our system contains seven (7) detectors and we have obtained the same number of RRAs, which means that our model is correct, therefore the rule: n number of detectors is equal to n number of RRAS was implemented (Djeziri and Ou. 2009; Busson 2002).
- The RRAs are structurally independent.
- We have an observable bond graph which implies: for each junction 0 or 1 with one detector, corresponds one RRA.

FINDING THE FDI MATRIX

The detectability and isolability of the process compnents can be tested in using the RRAs generated by ModelBuilder of SYMBOLS 2000. For this, we must first exclude components that are, according to the specifications laid down, supposedly infallible. In our case we assume that the input voltage of the machine is excluded from the specifications.

RESULTS AND DISCUSSION

The matrix of failure signature (also called: matrix for detection and isolation of faults -FDI-) obtained is represented in figure 6.

Monitorability Analysis

	M_b	I_b	R1	R2	R3	R4	R5	R6	R7
Df2_Measurement	1	1	1	0	1	0	0	0	1
Df3_Measurement	1	1	1	0	1	1	1	1	0
Df4_Measurement	1	1	0	0	0	0	1	0	0
De1_Measurement	1	0	1	1	0	1	0	0	0
Df6_Measurement	1	1	0	1	0	1	0	0	0
Df5_Measurement	1	1	0	0	0	0	0	1	0
Df1_Measurement	1	1	0	0	0	0	0	0	1
Réduct	1	1	1	0	0	1	1	1	0
VisEcrou	1	0	1	1	0	1	0	0	0
Moteur	1	1	1	0	1	0	0	0	0

Figure 6: FDI matrix generated by the software.

On the matrix of figure 6 displayed the variables are measures, sources and components of the process. On this window, it was specified that the components found infallible in the scope of process, so they will not be displayed.

It should be noted that R_1,R_2,..., R_7 represent the corresponding residues to RRAs and (M_b, I_b) are respectively the detectability and isolability of failures. The rows of the matrix are the signatures of the components (i.e. dependence of residuals in relation to failures of components). A value 1 means that the failure of the component theoretically influence on one response of (or several) residue(s), 0 else. When the variable associated with a component appears in at least one residue, then its failure is detectable (M_b= 1). If the signature of a component is unique (strictly different to others signatures) her failure is isolated (I_b= 1).

From the matrix of figure 6, we note that:

- All values of the column M_b are equal to 1, therefore all failures of the system can be detected.

- On the other hand, the signatures of detector De1 and the ensemble Screw/Nut are identical which means that defects affecting these components can not be isolated therefore the torque sensor can not contribute effectively to the supervision of the part Screw/Nut.
- The motor and reductor are supervisable as their signature is different.
- The set Screw/Nut is not entirely supervised.

It is important to note that the matrix of failures signatures built from the causal paths is a configuration (or operation mode) well definite and therefore the associated model. The form of equations for each component bond graph is the same throughout the period of operation in a given configuration.

CONCLUSION AND FURTHER WORK

In this study, we propose a solution for the integrated supervision of this mechatronic system technically feasible and economically realizable to be integrated into production lines, to assist the maintenance operators. The advantage of this method lies in :

- The possibility to have an integrated supervision system adapted for monitoring the parameters of the machine in real time.
- Direct generation of the FDI matrix signature in real time.
- Versatile method for modification of the parameters of the machine.

Since we found that all the faults at the ensemble Screws/Nuts are not entirely monitoring, further study may lead to the solution taking into account the following parameters:

- Incorporate into the calculations of the mechanical wear (reductor, Screw/Nut, gyrator of the motor).
- Incorporate into the integrated conception of supervision the tool carry.
- Installation of a control system modeled by bond graph.

REFERENCES

Bishop, R.H. 2006. "Mechatronics : An introduction". *Taylor and Francis Group*. USA, 1-10.

Borutzky, W. 2009. "Bond graph modelling and simulation of multidisciplinary systems : An introduction". *Simulation Modelling Practice and Theory*, vol. 17, no. 1, 3-21.

Busson, F. 2002. "Les bond graphs multi-énergie pour la modélisation et la surveillance en génie des procédés". *Doctorate thesis*, Laboratoire d'Automatique et d'Informatique Industrielle de Lille, France, 97-109.

Cocquempot, V. 2004. "Contribution à la surveillance des systèmes indutriels". *HDR Thesis*, IUT de Lille, France.

Djeziri, M.A. 2007. "Diagnostic des systèmes incertains par l'approche bond graph". *Doctorate thesis*, Laboratoire d'Automatique et Informatique Industrielle de Lille, France.

Djeziri, M.A., B. Ould Bouamama, and R. Merzouki. 2009. "Modelling and robust FDI of steam generator using uncertain bond graph model". *Process Control*, vol. 19, no. 1, 149-162.

Medjaher, K., A.K. Samantaray, B. Ould Bouamama, and M. Staroswiecki. 2006. "Supervision of an industrial steam generator. Part II: Online implementation". *Control Engineering Practice*, vol. 14, no. 1, 85-96.

Mellal, M.A. 2009. "Modélisation et simulation pour la conception integrée de supervision d'une application mécatronique par l'outil bond graph". *Master's research degree*, Faculté des Sciences de l'Ingénieur, M'Hamed Bougara University, Boumerdès, Algeria.

Ould Bouamama, B. 2002. "Modélisation et supervision des systèmes en génie des procédés : Approche Bond Graph". *HDR Thesis*. Laboratoire d'Automatique et Informatique Industrielle de Lille USTL, France.

Ould Bouamama, B. and G.Dauphin Tanguy. 2006. "Modélisation par Bond Graph : Eléménts de Base pour l'Energétique". *Techniques de l'Ingénieur*, BE 8 280, France.

Samantaray, A.K. and B. Ould Bouamama. 2008. "Model based Process Supervision : A Bond Graph Approach". *Springer-Verlag*, London. 489 p, 2008.

Vergé, M. and D. Jaume. 2004. "Modélisation structurée des systèmes avec les Bond Graphs". *Editions TECHNIP*, France, 273-287.

AUTHOR BIOGRAPHY

MELLAL Mohamed Arezki was born in Bordj Ménaiel, Wilaya of Boumerdès, ALGERIA and went to the M'Hamed Bougara University of Boumerdès (Faculty of Engineering Sciences), where he studied mechatronics and obtained his master's research degree in 2009. Since January 2010 he prepare his doctorate theses in the laboratory of LMSS. His research interests include modeling of complex systems, dependability of industrial systems and study of industrial risks.
His e-mail address is : `mellal-mohamed@umbb.dz`