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

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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).

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 reducer 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 $\text{Pos}(t)$, view figure 1.

![Figure 1: Presentation of the table.](image)

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

<table>
<thead>
<tr>
<th>Value</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_v = 0.47$</td>
<td>Constant of the motor</td>
<td>(rad/s)/v</td>
</tr>
<tr>
<td>$L = 0.0019$</td>
<td>Inductance of the motor</td>
<td>H</td>
</tr>
<tr>
<td>$R = 0.61$</td>
<td>Resistance of the armature</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>$J = 0.01$</td>
<td>Inertia of the rotating part</td>
<td>kg·m²</td>
</tr>
<tr>
<td>$n = 0.5$</td>
<td>Reduction ratio</td>
<td></td>
</tr>
<tr>
<td>$h = 0.01$</td>
<td>Pitch of the screw</td>
<td>m/rad</td>
</tr>
<tr>
<td>$M = 8$</td>
<td>Mass of the table</td>
<td>Kg</td>
</tr>
<tr>
<td>$f = 6000$</td>
<td>Viscous friction</td>
<td>N·s/m</td>
</tr>
<tr>
<td>$k = 300000$</td>
<td>Stiffness</td>
<td>N·m/rad</td>
</tr>
</tbody>
</table>

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:

![Bond graph model](image)

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

\[
\begin{aligned}
 f_1 &= f_3 = f_4 = f_2 \\
 e_2 &= V_2 - e_3 - e_4
\end{aligned}
\]  

(1)

Junction 1 : \(\omega_1\)

\[
\begin{aligned}
 f_5 &= f_7 = f_6 \\
 e_6 &= e_5 - e_7
\end{aligned}
\]  

(3)

Junction 0

\[
\begin{aligned}
 e_8 &= e_{10} = e_9 \\
 f_9 &= f_8 - f_{10}
\end{aligned}
\]  

(5)

Element 1 : M

\[
\begin{aligned}
 p_1 &= e_2 \\
 f_2 &= \frac{1}{L} \times p_2 \\
 e_7 &= m_1 \times e_6 \\
 f_6 &= \frac{1}{L} \times p_6 \\
 e_5 &= r \times f_4 \\
 e_4 &= r \times f_5
\end{aligned}
\]  

(9)  
(10)  
(11)  
(12)  
(13)

Transformer TF : \(m_1\)

\[
\begin{aligned}
 e_{11} &= \frac{1}{m_2} \times e_2 \\
 f_6 &= \frac{1}{L} \times p_2
\end{aligned}
\]  

(14)  
(15)

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).

![Equations](image)

Figure 3: Equations generated by the software.

CONSTRUCTION OF CAPSULES TO GENERATE THE FDI MATRIX

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.

![Expresssions](image)

Please note: ‘d’ represents the term d(P6)=n1*F3/\(M_3-n_1*n_3*K_{11}*Q_{11}\)

\[
d(F14)=K_{11}*Q_{11}-R_{13}*F14/M_{14}
\]

\[
d(F3)=SE1-R2*F3/M3-n1*F6/M6
\]

\[
d(Q11)=F14/M14+m3*m3*F6/M6
\]
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.

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).

FINDING THE FDI MATRIX

The detectability and isolability of the process components 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.

<table>
<thead>
<tr>
<th></th>
<th>$N_D$</th>
<th>$I_D$</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$R_3$</th>
<th>$R_4$</th>
<th>$R_5$</th>
<th>$R_6$</th>
<th>$R_7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Di2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Di3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Di4</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Di6</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Di5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Di1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Reduct</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>VisEcrou</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Moteur</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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 $(M_D, I_D)$ 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 $(I_D=1)$. If the signature of a component is unique (strictly different to others signatures) her failure is isolated $(I_D=1)$.

From the matrix of figure 6, we note that:

- All values of the column $M_D$ 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


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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.

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