Functionability Analysis of Redundant Mechatronic Systems

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- Redundant Mechatronic Systems
- Research Issues
- Research Gap
- Research Contribution
- Positioning of the work

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- Problem Formulation
- Methodology

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Introduction:
PSPC VASCO Project 15-19, Gaussian-BA Systèmes-LS2N-CRISTAL
Introduction

- Redundancy is a common approach to improve the reliability of critical systems such as aerospace, chemical plants, nuclear plants, autonomous vehicles, etc.

- Redundancy can be in terms of actuators, sensors, and other critical components of a system.

- Due to redundancy, a system may reconfigure its structure when required, in order to achieve its intended function.
In this work, we focus only on mechatronic systems, which are multi-domain in nature and possess some intelligence using mechanical, electrical, electronics and computer based control and supervision systems.

For safe and reliable autonomous operations of such systems, it is necessary to have some redundancy in the system.

A redundant mechatronic system can have multiple configurations due to redundancy.
As discussed before that a redundant system can have multiple configurations, and these configurations may have different levels of performance. In case of a faulty situation, the following issues may be raised:

- Which configuration should be used among all available configurations?

- Whether the redundant system can still perform its intended function using its other available configurations?

- If yes, then what will be the performance level of the reconfigured system?
Based on the research issues discussed, the research gap can be stated as follows: *it is necessary to evaluate the functional performance level of each possible configuration of a redundant system.*

The interest of evaluating the functional performance level is to suggest that which configuration of a redundant system should be selected among all available configurations of the system, when subjected to an instantaneous fault.
Research Contribution

• A new indicator called *functionability* is proposed, which evaluates the functional performance level of each possible configuration of a redundant mechatronics system.

• Furthermore, it is combined with the model-based FDI in order to develop a unified analysis called *functionability analysis* for fault detectability, fault isolability, and system functionability.

• Finally, the proposed functionability analysis is applied to a heavy redundant mobile robot considering its multiple steering configurations.
Positioning of the work

In this work, we propose an off-line method to evaluate the performance levels of the various configurations of a redundant system, i.e., functionability.

The proposed system’s functionability is combined with the existing model-based FDI (Bouamama et al. 2003) in order to have a unified functionability analysis of redundant mechatronic systems.

Existing methods such as availability, maintainability, recoverability, etc. do not evaluate the performance levels of various configurations of a redundant system.
Literature Review on Development of BG Theory

1) The first contribution with respect to existing solutions in redundant mechatronic systems.

2) The second contribution with respect to existing solutions in model-based FDI is to combine the proposed functionability in order to have a unified method for the functionability analysis of redundant systems.

3) Furthermore, the functionability analysis is utilized for the online reconfiguration of a faulty redundant system.

The proposed functionability analysis is applied to the steering system of a vehicle, where a redundant steering system represents a hybrid system with continuous and discrete dynamics. A hybrid system changes between its discrete modes, which makes its diagnosis complex. In [39], the BG model was developed for robust diagnosis [33], [34] and for multiple faults in model-based FDI. In [32], a mode tracking method was developed in [32]. HBG was further developed for the presence of the different modes in hybrid systems, their issue of causality change in HBG, and global ARRs (GARRs) are proposed for the hybrid dynamical systems [31]. Due to the nature of dynamical systems, hybrid BG (HBG) was proposed in [30] by solving the diagnostic HBG (DHBG) was proposed in [30] by solving the issues of causality change in HBG, and global ARRs (GARRs) are proposed for the hybrid dynamical systems [31]. Due to the nature of causality change in HBG, and global ARRs (GARRs) are proposed for the hybrid dynamical systems [31].

Diagnostic HBG (DHBG) was proposed in [30] by solving the issues of causality change in HBG, and global ARRs (GARRs) are proposed for the hybrid dynamical systems [31]. Due to the nature of causality change in HBG, and global ARRs (GARRs) are proposed for the hybrid dynamical systems [31].

The present work

The contributions of this article can be summarized as follows.

- Evaluation of model-based diagnosis for functionability analysis of redundant systems
- Integration of functionability with BG/HBG based diagnosis
- Robust diagnosis based on LFT-BG (parametric un.)
- Robust diagnosis using LFT-BG (parametric & measurement un.)
- Robust diagnosis based on HBG (parametric & measurement un.)
- Discontinuity in BG
- Hybrid BG (HBG)
- HBG based Diagnosis

Software Tools

- CAMP-G, SYMBOLS, 20-SIM...
- Granda [36]; Mukherjee and Samantaray [37]; Broenink [38]...
General Structure of a Redundant Mechatronic Systems

\[ \text{Co}_m \] – \text{m}^{th} \text{ component of the system;}
\[ S_p \] – \text{p}^{th} \text{ configuration of the system;}
\[ F_{m,p} \] – functionality of \text{p}^{th} configuration corresponding to a faulty \text{m}^{th} component
Here, we define functionability as follows:

- The functionality of a system’s configuration is the measure that how well the configuration can perform with reference to the desired performance of the system, based on the desired values of a set of criteria.

The structure of a redundant system can be reconfigured based on selecting the optimal configuration with maximum functionability, when subjected to a fault. The optimization problem can be stated as follows:

\[
\max_{S_p} F_{1\ldots m,p} = \sum_{i=1}^{k} C_{i,p}(w_i, d_i, a_{i,p}, S_p) \\
\text{s.t.} \quad 0 < w_i < 1
\]

\[C_{i,p}\] represents the performance of the \(i\)th criterion for the \(p\)th configuration of the system. For maximum criterion, \(C_{i,p} = \frac{w_i a_{i,p}}{d_i}\) and for minimum criterion, \(C_{i,p} = \frac{w_i d_i}{a_{i,p}}\). \(w_i\) and \(d_i\) represent weight and the desired set value of the \(i\)th criterion.
Methodology

\[
\begin{align*}
\text{DBG/DHBG} & \rightarrow \text{ARRs/GARRs} & \rightarrow \text{FSM} & \rightarrow \text{Functionality (off-line)} & \rightarrow \text{FSMex for reconfiguration} \\
\text{BG based fault diagnosis (on-line)} & & & & \\
\end{align*}
\]

**Redundant system subjected to faults**

**DESCRIPTION OF THE PROPOSED FSMex**

| Co. | R₁ | R₂ | ... | Rₙ | Dₛ₁ | Dₛ₂ | S₁ | S₂ | ... | Sₚ | Fₛ₁ | Fₛ₂ | ... | Fₛₚ | Fₛ₂ |
|-----|----|----|-----|----|------|------|----|----|-----|----|------|------|-----|------|------|-----|
| Co₁ | B₁₁ | B₁₂ | ... | B₁ₙ | D₁₁ | D₁₂ | I₁₁ | I₁₂ | ... | I₁ₙ | F₁₁  | F₁₂  | ... | F₁ₙ  | F₁₂  |
| Co₂ | B₂₁ | B₂₂ | ... | B₂ₙ | D₂₁ | D₂₂ | I₂₁ | I₂₂ | ... | I₂ₙ | F₂₁  | F₂₂  | ... | F₂ₙ  | F₂₂  |
| ... |    |    |     |     |     |     |    |    |     |    |     |     |     |     |     |
| Coₘ | Bₘ₁ | Bₘ₂ | ... | Bₘₙ | Dₘ₁ | Dₘ₂ | Iₘ₁ | Iₘ₂ | ... | Iₘₙ | Fₘ₁  | Fₘ₂  | ... | Fₘₙ  | Fₘ₂  |

Réunion du GT S3
The proposed analysis is applied to the steering system of a heavy redundant mobile robot called Robutainer.
Focusing on steering systems in Robutainer, due to redundant actuations for steering (front and rear sides), three steering configurations \((p = 3)\) are possible:

i) steering of the front side only \((S_1)\),

ii) steering of the rear side only \((S_2)\), and

iii) steering of the both sides \((S_3)\).
The steering system of Robutainer is a mechatronic system with mechanical, electrical, and hydraulic components.

In addition, it represents a hybrid system combining continuous and discrete dynamics.

Therefore, the steering system represents a complex system with possibility of different components faults.
DHBG of the Steering System
The following important criteria are considered for Robutainer:

i) maximum safety $C_{1,p}$

ii) maximum mean velocity $C_{2,p}$

iii) minimum energy consumption $C_{3,p}$

Based on the above criteria, functionability of three configurations is evaluated using experimental data of Robutainer:

<table>
<thead>
<tr>
<th>$C_{i,p}$</th>
<th>$d_i$</th>
<th>$a_{i,1}$</th>
<th>$a_{i,2}$</th>
<th>$a_{i,3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{1,p}$ (%); $w_1 = 1$</td>
<td>$d_1 = 1$</td>
<td>$a_{1,1} = 0.9$</td>
<td>$a_{1,2} = 0.8$</td>
<td>$a_{1,3} = 1$</td>
</tr>
<tr>
<td>$C_{2,p}$ (m/s); $w_2 = 0.6$</td>
<td>$d_2 = 1.4$</td>
<td>$a_{2,1} = 1.3883$</td>
<td>$a_{2,2} = 1.3841$</td>
<td>$a_{2,3} = 1.3876$</td>
</tr>
<tr>
<td>$C_{3,p}$ (Joul); $w_3 = 0.8$</td>
<td>$d_3 = 4.0e5$</td>
<td>$a_{3,1} = 4.8306e5$</td>
<td>$a_{3,2} = 6.9610e5$</td>
<td>$a_{3,3} = 4.1231e5$</td>
</tr>
<tr>
<td>$F_{1\ldots m,p}$</td>
<td>$F_{1\ldots m,1} = 0.7191$</td>
<td>$F_{1\ldots m,2} = 0.6176$</td>
<td>$F_{1\ldots m,3} = 0.7902$</td>
<td></td>
</tr>
</tbody>
</table>

The generalized structure of a redundant system is shown in Fig. 2. In Fig. 2, at the abstract level so of the system's structure are generalized. The performance of the reconfigured system may be same or degraded. The performance level of the reconfigured system can be quantified. The rest of this article is organized as follows. Section II presents the proposed methodology is applied to a heavy redundant mobile robot using a complex hybrid mechanism of functionability analysis. In Section III, the proposed methodology is applied considering its multiple aspects. The main advantage of the proposed analysis is that it enables the performance to other allowed configurations. However, the functional performance at this level. At the middle level, there are calculated online by choosing the configuration with maximum functionability at any instant of time.

The parameters $F_{1\ldots m,p}$ are corresponding to a faulty component $S_m$ of the system, which a possible due to other reasons. In this case, none/some/all configurations may be calculated based on various important criteria for a system. If available configurations, then it can be considered as the optimal configuration because faulty component $Co_1$ in the system, despite this fault, if a configuration (say $Co_p$) has the maximum functionability ($F_{Co_p}$), it can be considered as the optimal configuration.

For functioning of a configuration, it is necessary that all the components of that configuration must be healthy. When the parameters $F_{1\ldots m,p}$ are set offline, then, optimal/best configuration ($Co_{opt}$) can be calculated online by choosing the configuration with maximum functionability ($F_{Co_{opt}}$) (for maximum criterion)

$$C_{i,p} = \frac{w_i a_{i,p}}{d_i}$$

(for maximum criterion)

or (for minimum criterion).

$$C_{i,p} = \frac{w_i d_i}{a_{i,p}}$$

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- Minimum energy consumption $C_{3,p}$

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FSMex enables to detect and isolate a component fault; in addition, it suggests that which configuration should be select based on maximum functionability.
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FSMex enables to detect and isolate a component fault; in addition, it suggests which configuration should be selected based on maximum functionality.

<table>
<thead>
<tr>
<th>Co.</th>
<th>Parameters</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>R10</th>
<th>Dｂ</th>
<th>Iｂ</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>(none)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co1</td>
<td>$R_M$ Motor resistance (1.5 Ω)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(none)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K_M$ Mot. constant (0.3 Nm/A)</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>1</td>
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<tr>
<td></td>
<td>$J_M$ Motor inductance (0.6 H)</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>1</td>
<td>0</td>
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<tr>
<td></td>
<td>$f_M$ Motor Friction (0.21 N-m-s/rad)</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td>1</td>
<td>0</td>
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</tr>
<tr>
<td>Co2</td>
<td>$V_P$ Pump constant (1.761e-5 m³/rad)</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(none)</td>
<td></td>
</tr>
<tr>
<td>Co3</td>
<td>$C_P$ Accumulator compliance (2.1739e9 Pa/m³)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(none)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{lf}$ Leakage in front pipeline (1e30 Pa-s/m³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
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<td>1</td>
<td>0</td>
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<tr>
<td></td>
<td>$R_{lr}$ Leakage in rear pipeline (1e30 Pa-s/m³)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>1</td>
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<td>1</td>
<td>0</td>
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</tr>
<tr>
<td>Co4</td>
<td>$R_{pf}$ Front valve resistance for port P to T (1e10 Pa-s/m³)</td>
<td>$a_{1f}$</td>
<td>$a_{1f}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.61</td>
<td>76</td>
<td>0</td>
<td>0.61</td>
<td>76</td>
<td>(S2)</td>
<td></td>
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<tr>
<td></td>
<td>$R_{pf}$ Front valve resistance for port P to A (1e10 Pa-s/m³)</td>
<td>$a_{2f}$</td>
<td>$a_{2f}$</td>
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</tr>
<tr>
<td></td>
<td>$R_{pf}$ Front valve resistance for port P to B (1e10 Pa-s/m³)</td>
<td>$a_{4f}$</td>
<td>$a_{4f}$</td>
<td></td>
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<tr>
<td></td>
<td>$R_{pf}$ Front valve resistance for port A to T (1e10 Pa-s/m³)</td>
<td>$a_{5f}$</td>
<td>$a_{5f}$</td>
<td></td>
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<tr>
<td></td>
<td>$R_{pf}$ Front valve resistance for port B to T (1e10 Pa-s/m³)</td>
<td>$a_{3f}$</td>
<td>$a_{3f}$</td>
<td></td>
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</tr>
<tr>
<td>Co5</td>
<td>$R_{pr}$ Rear valve resistance for port P to T (1e10 Pa-s/m³)</td>
<td>$a_{1r}$</td>
<td>$a_{1r}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>0</td>
<td>0.71</td>
<td>91</td>
<td>0</td>
<td>0</td>
<td>0.71</td>
<td>91</td>
<td>(S1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{pr}$ Rear valve resistance for port P to A (1e10 Pa-s/m³)</td>
<td>$a_{2r}$</td>
<td>$a_{2r}$</td>
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<td></td>
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<td>1</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>(S1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{pr}$ Rear valve resistance for port P to B (1e10 Pa-s/m³)</td>
<td>$a_{4r}$</td>
<td>$a_{4r}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(S1)</td>
<td></td>
</tr>
</tbody>
</table>
Application: Redundant Mobile Robot

Reconfiguration algorithm based on the functionality analysis.
The proposed methodology is verified through real-time co-simulation of Robutainer. The following five scenarios are considered:

i) Scenario I: Constant Valves Mode and No Fault

ii) Scenario II: Constant Valves Mode and Fault in an Electric Motor

iii) Scenario III: Constant Valves Mode and Fault in a Front Distributor Valve

iv) Scenario IV: Changing Valves Mode and No Fault

v) Scenario V: Changing Valves Mode and Fault in a Rear Hydraulic Motor
Results

Scenario I: Constant Valves Mode and No Fault

Scenario II: Constant Valves Mode and Fault in an Electric Motor
Results

Scenario III: Constant Valves Mode and Fault in a Front Distributor Valve

Scenario IV: Changing Valves Mode and No Fault
Results

Scenario V: Changing Valves Mode and Fault in a Rear Hydraulic Motor
Conclusions

• A method is proposed for the functionability analysis of redundant mechatronic systems, which can switch to different configurations according to a fault present in the system.

• Functionability analysis enables us to choose the best configuration of a redundant system from the available configurations at any point of time.

• The proposed approach is applied to a heavy redundant mobile robot having three steering configurations.

• The proposed algorithm evaluates the functionability of each configuration of Robutainer and suggests that which configuration should be selected when subjected to a component fault.

• The selected configuration is optimal based on the maximum value of functionability, which quantifies the performance level of the reconfigured system.
Publications


