Functionability Analysis of Redundant Mechatronic Systems

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Réunion S3, Paris
March 5, 2020

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Introduction:

PSPC VASCO Project 15-19, Gaussin-BA Systèmes-LS2N-CRIStAL

Introduction

- Redundancy is common approach to improve 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.

Redundant Mechatronic Systems

- In this work, we focus only on mechatronic systems, which are multi-domain in nature and posses 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.

Research Issues

- 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?

Research Gap

- 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.

Structural Analysis of Mechatronic Systems

On-line

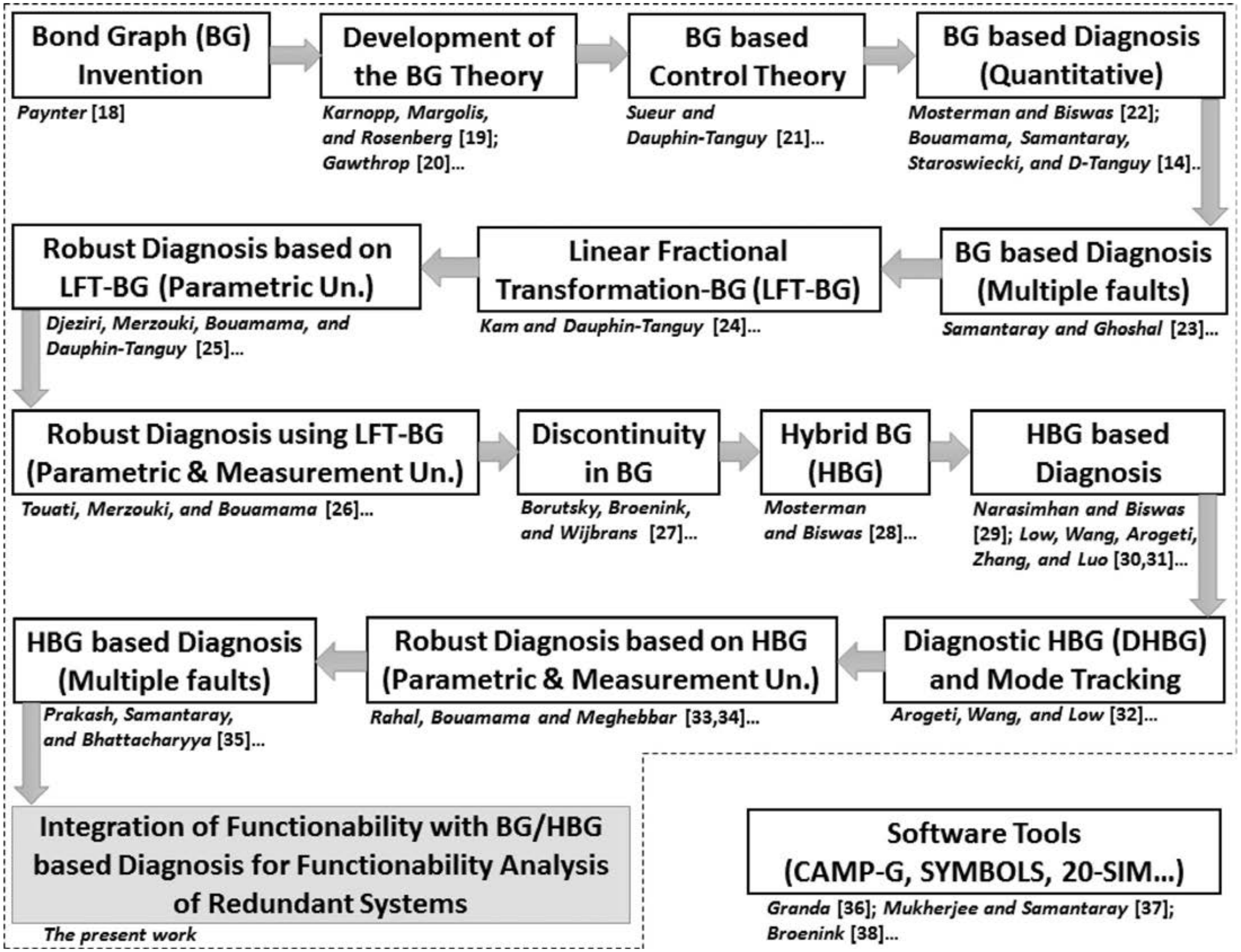
- **Fault Detectability and Isolability** (*Basseville 2001…*)
- **Fault Recoverability** (*Loureiro et al. 2012…*)
- ⋮

Off-line

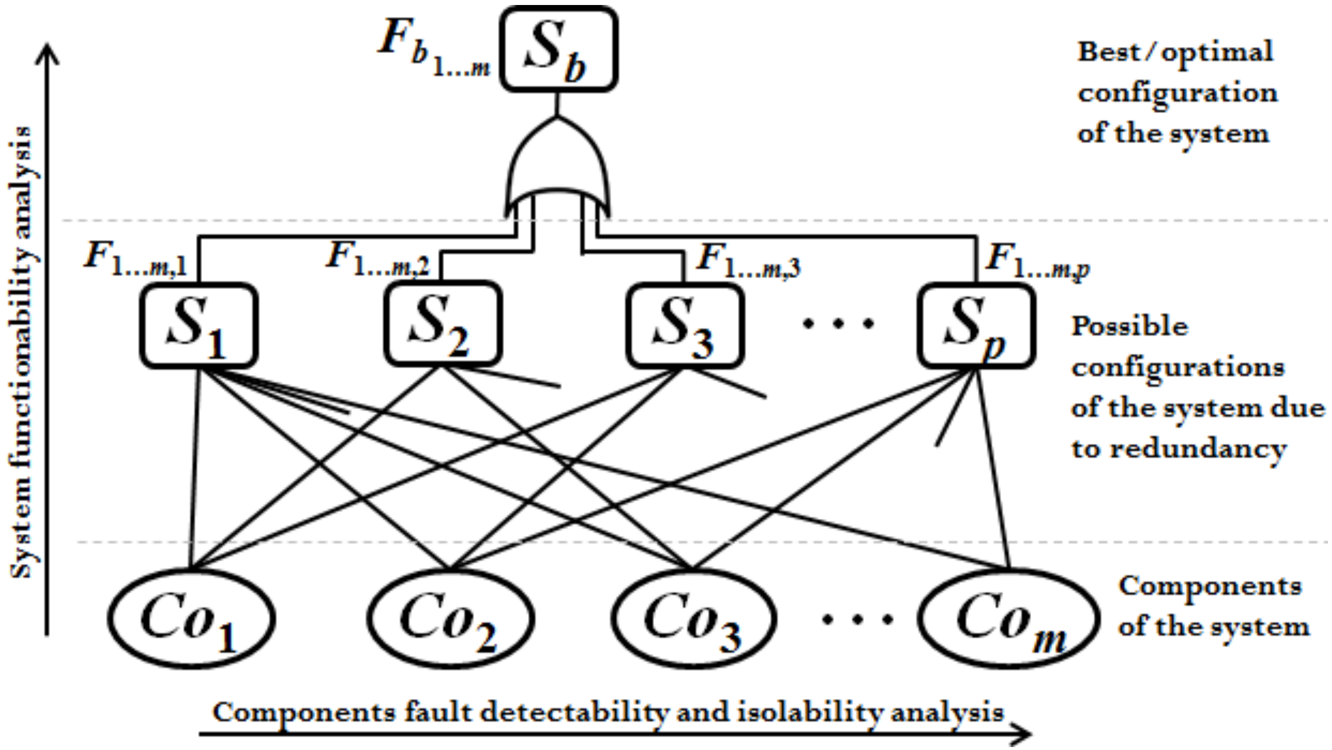
- **Controllability and Observability** (*Zhou 2015…*)
- **Reliability** (*Guo 2018…*)
- **Maintainability** (*Pomares 2014…*)
- **Availability** (*Khvatskin 2014…*)
- ⋮
- **Functionability** (*The present work*)

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



General Structure of a Redundant Mechatronic Systems



Co_m – *m^th^ component of the system;*

S_p – *p^th^ configuration of the system;* $S_p = \{\mathrm{Co}_2, \mathrm{Co}_3, \ldots, \mathrm{Co}_m\}$.

$F_{m,p}$ – *functionability of p^th^ configuration corresponding to a faulty m^th^ component*

Problem Formulation

- Here, we define functionability as follows:
  - *The functionability 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:

$$\max_{S_p} F_{1\ldots m,p} = \sum_{i=1}^{k} C_{i,p}(w_i, d_i, a_{i,p}, S_p)$$

$s.t.$

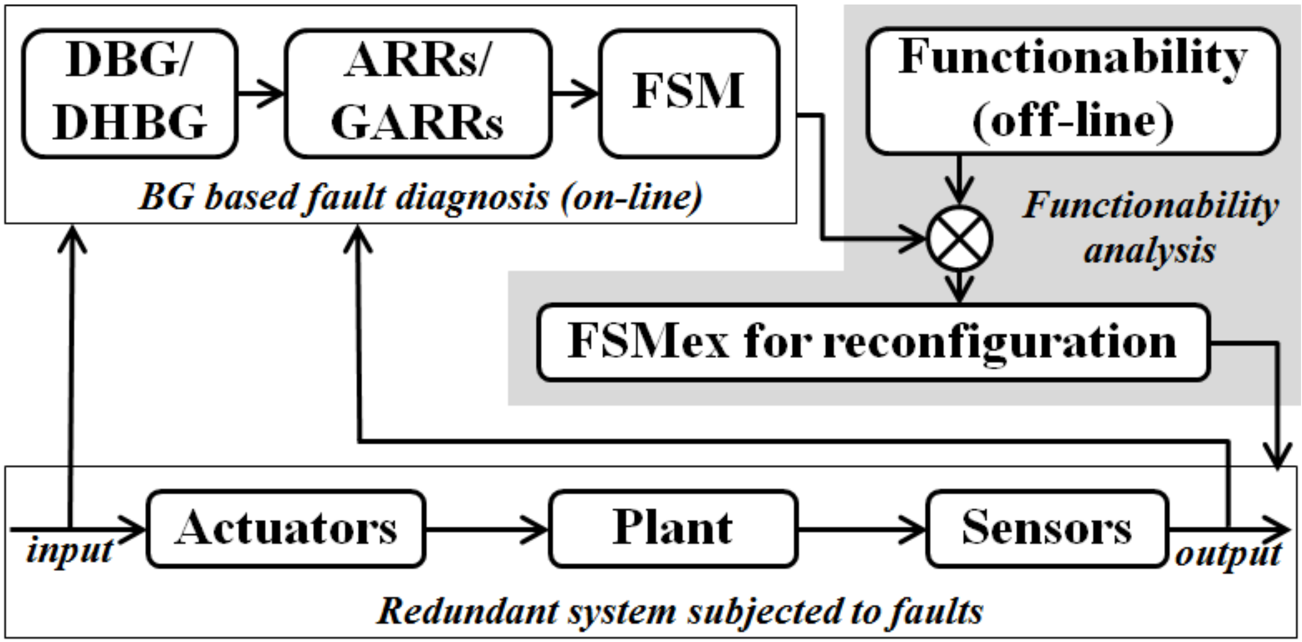
$$0 < w_i < 1$$

$C_{i,p}$ represents the performance of the ith criterion for the pth configuration of the system

$$C_{i,p} \begin{cases} = \frac{w_i a_{i,p}}{d_i} \text{(for maximum criterion)} \\ = \frac{w_i d_i}{a_{i,p}} \text{(for minimum criterion)}. \end{cases}$$

w_i and d_i represent weight and the desired set value of the ith criterion.

Methodology



DESCRIPTION OF THE PROPOSED FSMEX

Co.	R_1	R_2	...	R_n	D_b	I_b	S_1	S_2	...	S_p	F_b
Co_1	$B_{1,1}$	$B_{1,2}$	$\cdots$	$B_{1,n}$	D_{b_1}	I_{b_1}	$F_{1,1}$	$F_{1,2}$	$\cdots$	$F_{1,p}$	F_{b_1}
Co_2	$B_{2,1}$	$B_{2,2}$	$\cdots$	$B_{2,n}$	D_{b_2}	I_{b_2}	$F_{2,1}$	$F_{2,2}$	$\cdots$	$F_{2,p}$	F_{b_2}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
Co_m	$B_{m,1}$	$B_{m,2}$	$\cdots$	$B_{m,n}$	D_{b_m}	I_{b_m}	$F_{m,1}$	$F_{m,2}$	$\cdots$	$F_{m,p}$	F_{b_m}

Application: Redundant Mobile Robot

- The proposed analysis is applied to the steering system of a heavy redundant mobile robot called Robutainer.

(a) Robutainer autonomous redundant vehicle

(b) Loading and discharging operation in Dublin port

(c) Robutainer with Lateral movement

(d) Robutainer in dual steering in Oostende port

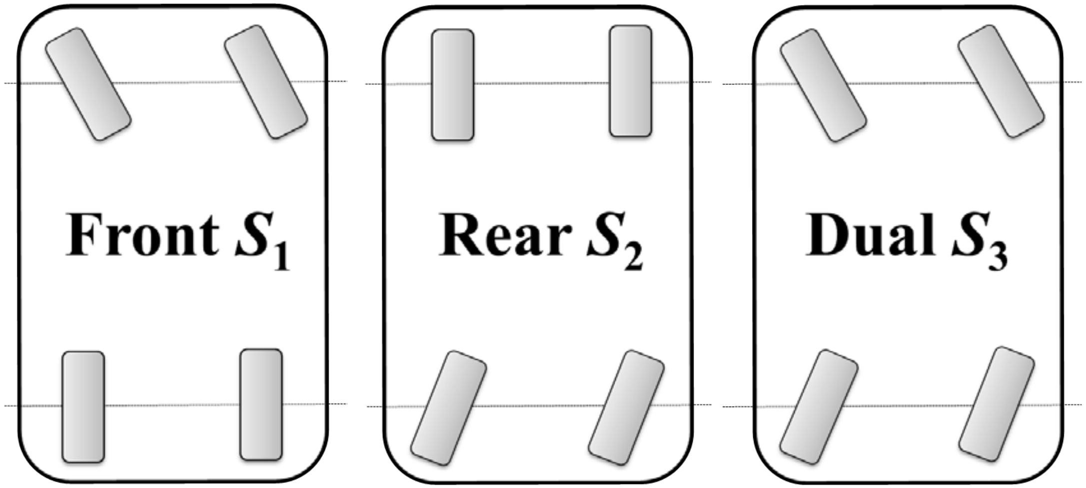
Application: Redundant Mobile Robot

Focusing on steering systems in Robutainer, due to redundant actuations for steering (front and rear sides), three steering configurations (p = 3) are possible:

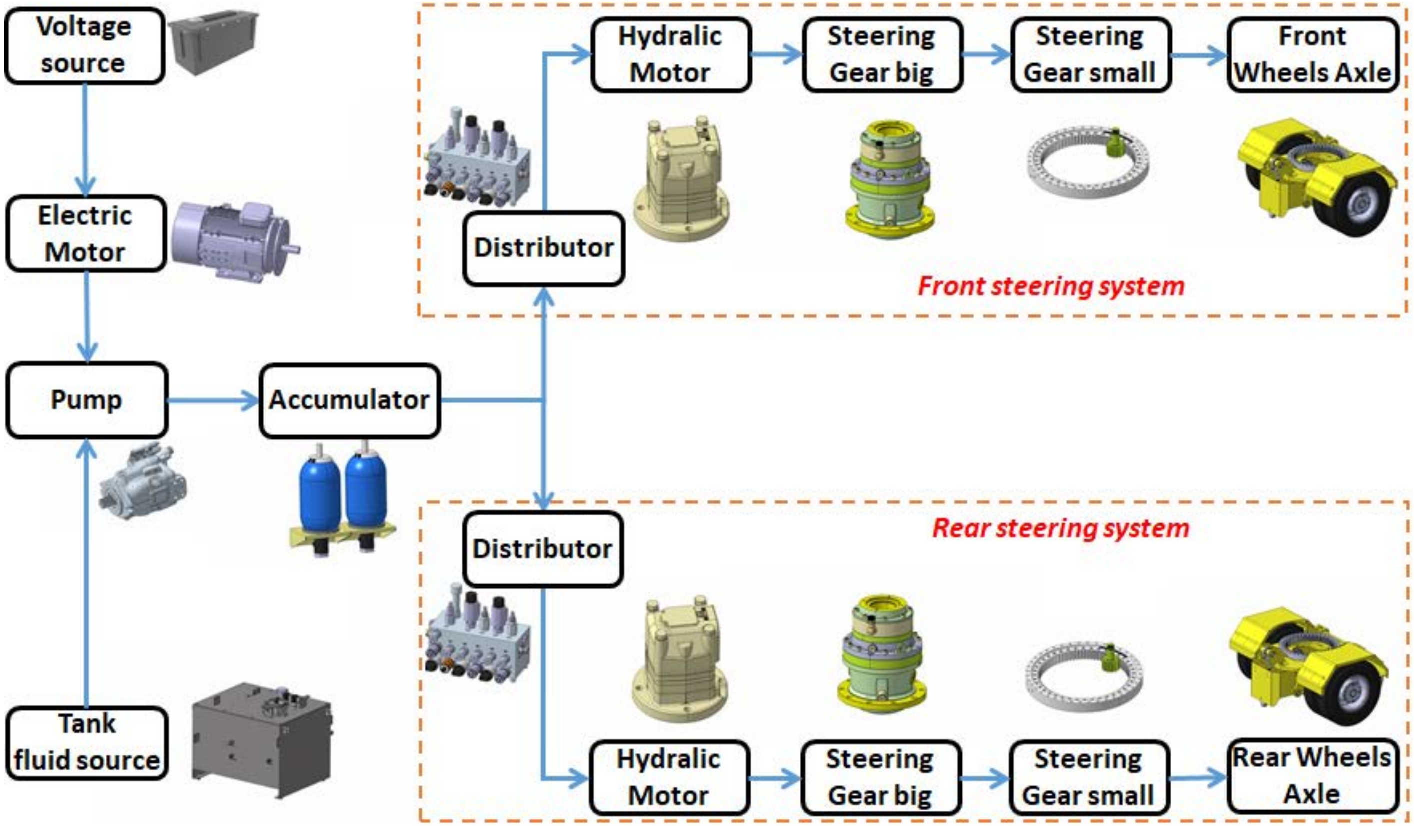
i) steering of the front side only (S_1),

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

iii) steering of the both sides (S_3).

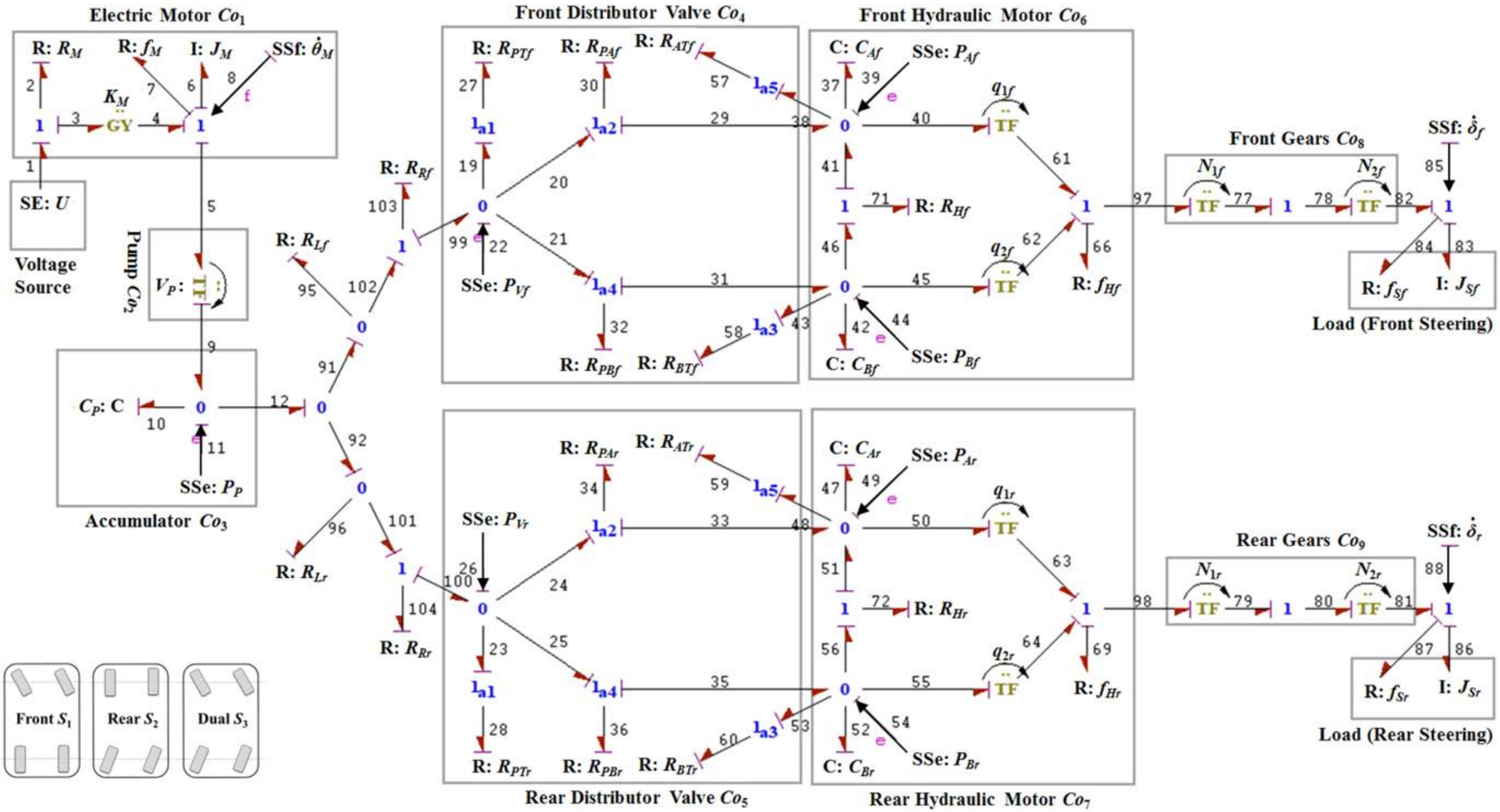


Application: Redundant Mobile Robot



- The steering system of Robutainer is a mechatronic system with mechanical, electrical, and hydraulic components.
- In addition, it represents to 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



Application: Redundant Mobile Robot

- 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 $C_{3,p}$

$$C_{i,p} \begin{cases} = \frac{w_i a_{i,p}}{d_i} \text{ (for maximum criterion)} \\ = \frac{w_i d_i}{a_{i,p}} \text{ (for minimum criterion).} \end{cases}$$

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

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

Application: Redundant Mobile Robot

- Based on the dynamic model-based FDI method, an extended fault signature matrix (FSMex) is developed.

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

Applicati

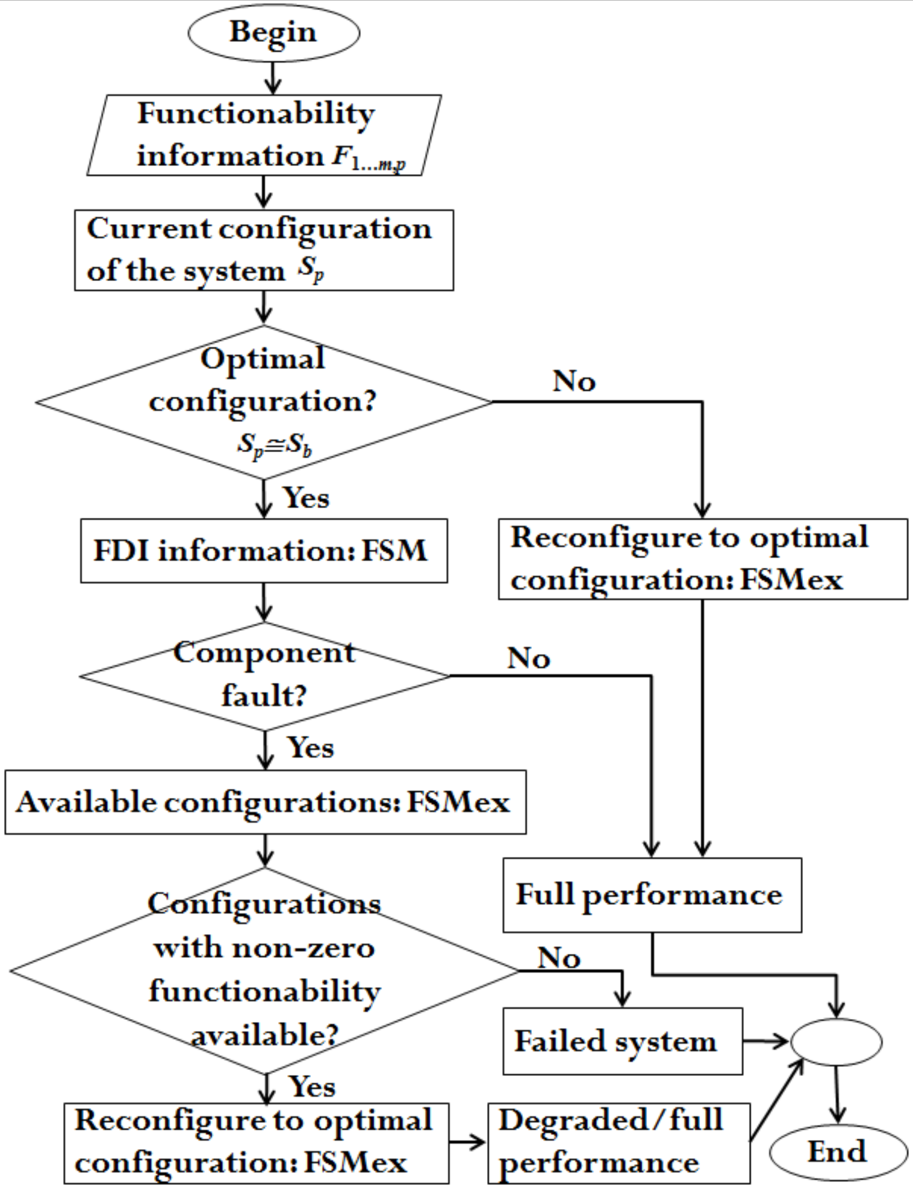
- Based on FDI met signature develope

- FSMex en componen suggests should be functional

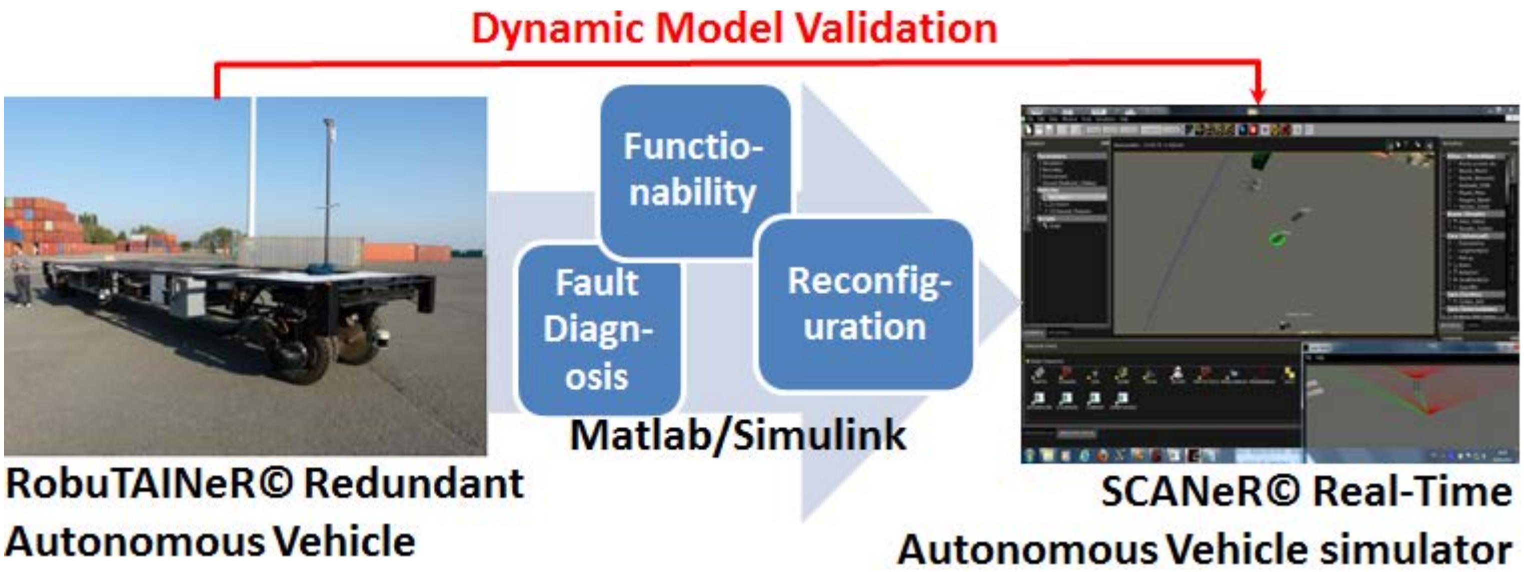
Co.	Parameters	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	D_b	I_b	I_{bc}	C_1	C_2	C_3	F_b
Co_1	R_M Motor resistance (1.5 Ω)	1										1	0	1	0	0	0	0 (none)
	K_M Mot. constant (0.3 Nm/A)	1										1	0					
	J_M Motor inductance (0.6 H)	1										1	0					
	f_M Motor Friction (0.21 N-m-s/rad)	1										1	0					
Co_2	V_P Pump constant (1.761e-5 m^3/rad)	1	1									1	1	1	0	0	0	0 (none)
Co_3	C_P Accumulator compliance (2.1739e9 Pa/m^3)		1									1	0	1	0	0	0	0 (none)
	R_{Lf} Leakage in front pipeline (1e30 Pa-s/m^3)		1									1	0					
	R_{Lr} Leakage in rear pipeline (1e30 Pa-s/m^3)		1									1	0					
Co_4	R_{PTf} Front valve resistance for port P to T (1e10 Pa-s/m^3)			a_{1f}								a_{1f}	a_{1f}	1	0	0.6176	0	0.6176 (S_2)
	R_{PAf} Front valve resistance for port P to A (1e10 Pa-s/m^3)			a_{2f}	a_{2f}							a_{2f}	a_{2f}					
	R_{PBf} Front valve resistance for port P to B (1e10 Pa-s/m^3)			a_{4f}		a_{4f}						a_{4f}	a_{4f}					
	R_{ATf} Front valve resistance for port A to T (1e10 Pa-s/m^3)				a_{5f}							a_{5f}	a_{5f}					
	R_{BTf} Front valve resistance for port B to T (1e10 Pa-s/m^3)					a_{3f}						a_{3f}	a_{3f}					
Co_5	R_{PTr} Rear valve resistance for port P to T (1e10 Pa-s/m^3)							a_{1r}				a_{1r}	a_{1r}	1	0.7191	0	0	0.7191 (S_1)
	R_{PAr} Rear valve resistance for port P to A (1e10 Pa-s/m^3)							a_{2r}	a_{2r}			a_{2r}	a_{2r}					
	R_{PBr} Rear valve resistance for							a_{4r}		a_{4r}		a_{4r}	a_{4r}					

Application: Redundant Mobile Robot

Reconfiguration algorithm based on the functionability analysis.



Real Time Co-simulation



- 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

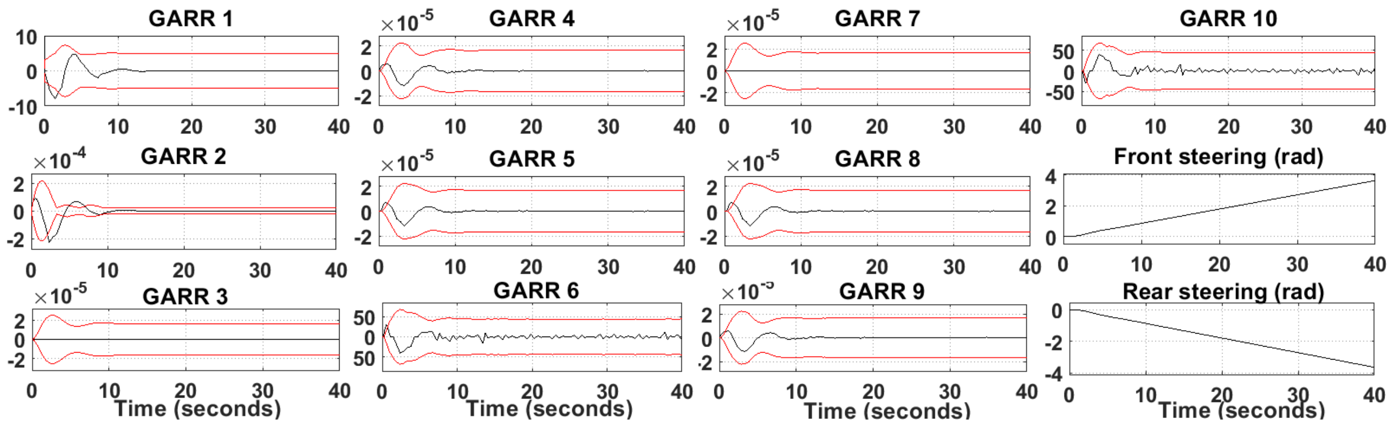
  iii) Scenario III: Constant Valves Mode and Fault in a Front Distributor Valve

  iv) Scenario IV: Changing Valves Mode and No Fault

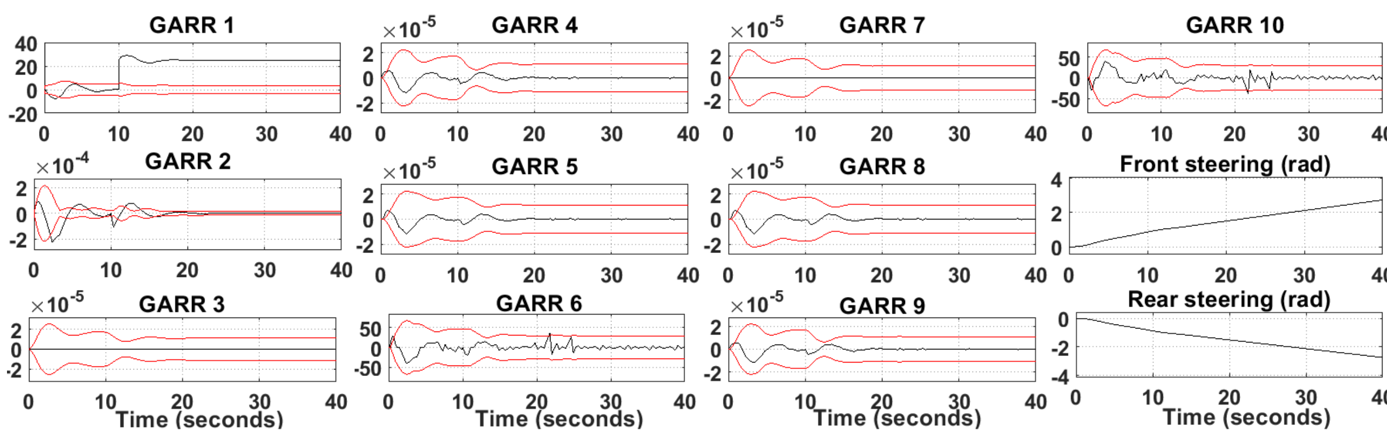
  v) Scenario V: Changing Valves Mode and Fault in a Rear Hydraulic Motor

Results

Scenario I: Constant Valves Mode and No Fault

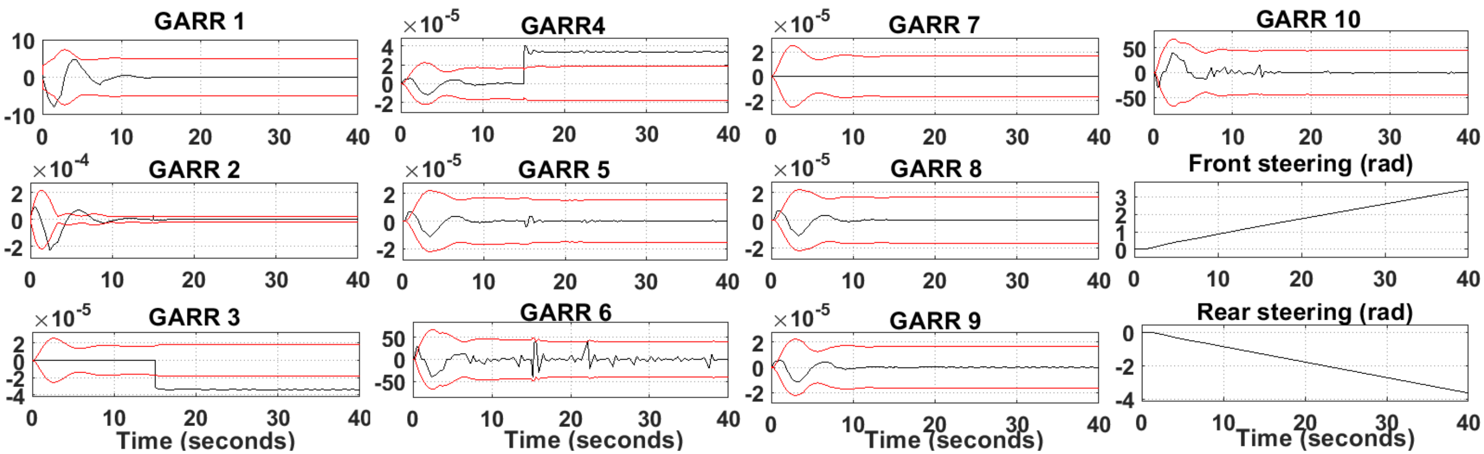


Scenario II: Constant Valves Mode and Fault in an Electric Motor

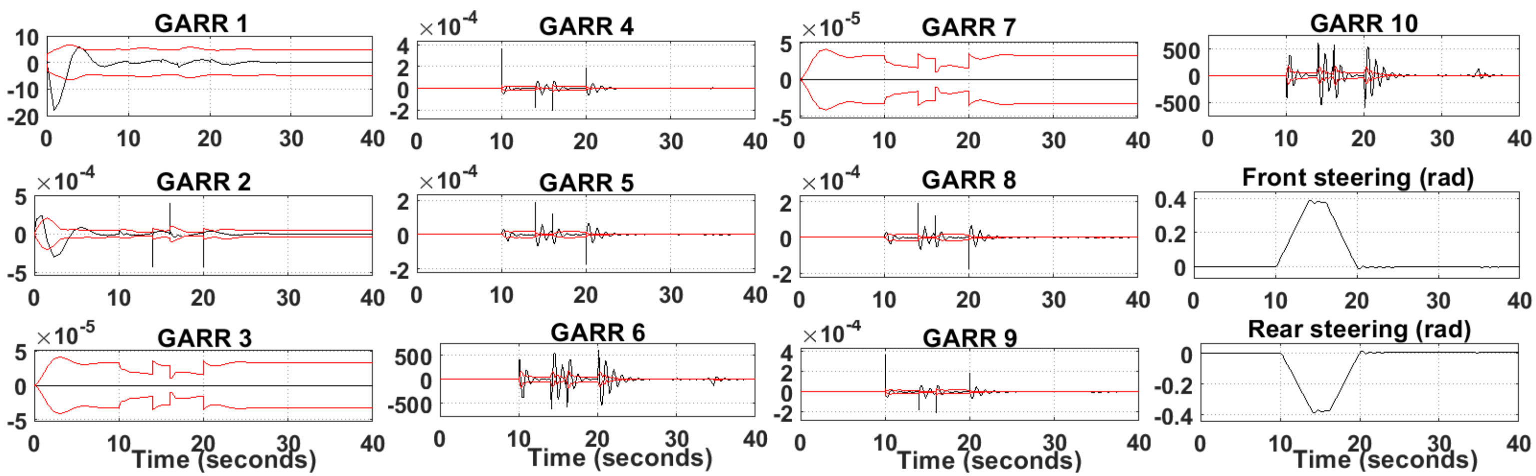


Results

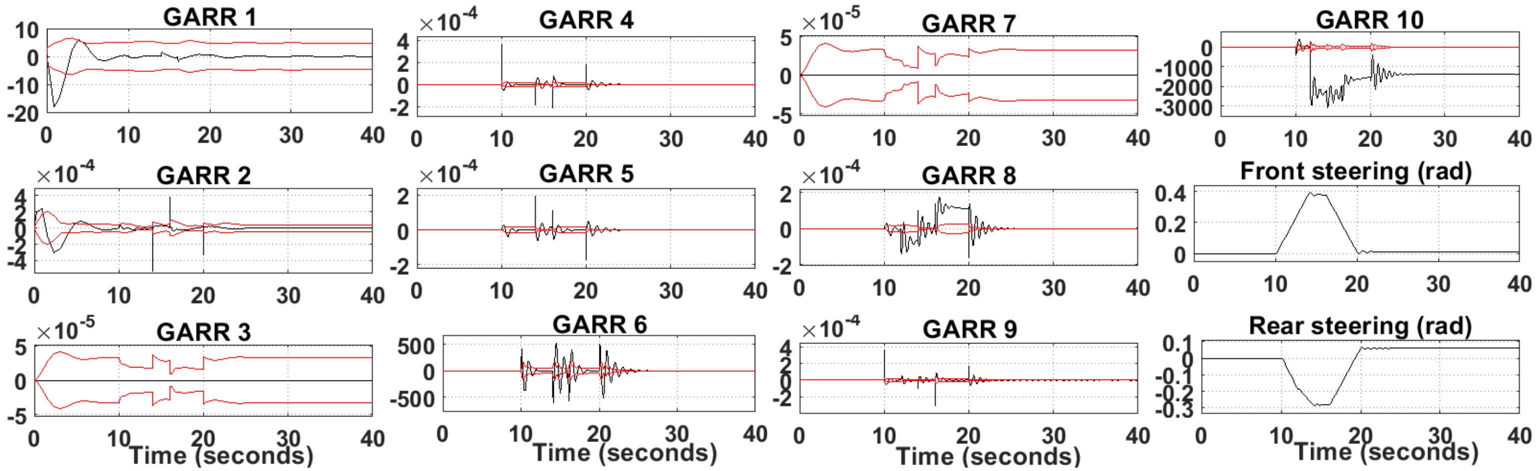
Scenario III: Constant Valves Mode and Fault in a Front Distributor Valve



Scenario IV: Changing Valves Mode and No Fault



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

- Kumar, P., Bensekrane & Merzouki, R. (2020). Reconfiguration Strategy for a Heavy Mobile Robot with Multiple Steering Configurations, IFAC WC, Berlin, Germany.

- Kumar, P., Bensekrane, I., Conrard, B., Toguyeni, A., & Merzouki, R. (2019). Functionability Analysis of Redundant Mechatronic Systems in Bond Graph Framework. *IEEE/ASME Transactions on Mechatronics*, Volume: 24 (6), pp. 2465 - 2476.

- Kumar, P., Bensekrane, I., Riad, C., Conrard, B., Toguyeni, A., & Merzouki, R. (2019, September). Functionability Analysis of Redundant Systems having Multiple Configurations. In *2019 4th Conference on Control and Fault Tolerant Systems (SysTol)* (pp. 282-287). IEEE.

IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 24, NO. 6, DECEMBER 2019 2465

Functionability Analysis of Redundant Mechatronic Systems in Bond Graph Framework

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***Abstract*—A redundant system can continue to perform its intended function in a faulty condition using its multiple configurations. However, the performance may be degraded due to varying functional performance of each configuration. Thus, redundancy improves the reliability of a system. This article presents a method to analyze the level of functional performance of a redundant system with faults. In this article, a new indicator, called functionability, is proposed for a class of redundant systems, namely engineering mechatronic systems. The developed method is integrated with the bond graph based theory of fault diagnosis, in order to develop a methodology for the functionability analysis of redundant systems. The developed methodology is applied on the steering function of a heavy redundant mobile robot called Robutainer. Due to redundancy, Robutainer shows multiple steering configurations, namely front, rear, and dual. The approach is validated through experiments and real-time cosimulation of Robutainer for trajectory tracking in a port environment and considering different components faults in its multidomain hybrid steering system.**

***Index Terms*—Bond graph (BG), fault diagnosis (FD), functionability, hybrid systems, mobile robots, redundant systems.**

I. Introduction

REDUNDANCY is common approach to improve reliability of critical systems, such as aerospace, chemical plants, nuclear plants, and autonomous vehicles [1], [2]. A redundant system can have multiple configurations according to the redundancy present in the system. The redundant system may reconfigure its structure when required, based on the different available configurations, in order to achieve its intended function. However, these configurations may have different levels of performance, and it is required to choose the best configuration based on the performance level. Therefore, it is necessary to quantify the functional performance level of each configuration of a redundant system. In the present work, we focus only on redundant mechatronic systems.

Structural analysis of mechatronic systems can be performed: online during operational phase, such as fault detectability, isolability, and recoverability; and offline during design phase, such as system controllability, observability, reliability, maintainability, and availability. Fault detectability concerns the activities to determine if the system dynamics has deviated beyond an acceptable limit from its normal operation model. If an unacceptable system behavior is detected then an alarm is declared, then the objective of isolability is to locate one or more faulty components in the system [3]. Fault recoverability analysis consists of studying the conditions under which a system is able to achieve its objectives, even when subjected to a fault [4]. System controllability and observability concern the activities to determine if there are sufficient input actuators and output sensors in the system to control and measure all of its states [5]. Reliability concerns with the ability of a system to perform its intended functions under certain conditions for a specified time [6], whereas maintainability concerns about the activities to repair or replace faulty components of the system [7]. Availability of a repairable system represents that it is operational at any instant of time for a given set of conditions [8].

According to IEC 61508 standard, functional safety is important for intelligent systems [9]. Redundancy (redundancy of actuations, sensors, and/or subsystems) improves the functional safety and reliability of such systems. Redundant mechatronic

Reconfiguration Strategy for a Heavy Mobile Robot with Multiple Steering Configurations

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Abstract: A redundant robot can complete a given task even in a faulty situation using its alternative configurations. This paper presents a reconfiguration strategy for a redundant heavy mobile robot called Robutainer. It is a four wheeled mobile robot, which is used to transport 40 feet container in port terminals. Robutainer has redundant steering actuations for the front and rear sides, due to this redundancy, it shows four steering configurations namely, dual, front, rear, and skid. Thus, Robutainer can reconfigure between its four steering configurations when subjected to a fault in the steering system. But, it is necessary to detect and isolate a fault in the steering system; subsequently, the robot can be reconfigured according to the available steering configurations. The steering system of Robutainer is a complex multi-domain system with hybrid dynamics. In this work, a graphical modeling approach Bond Graph (BG) is used to develop the fault detection and isolation (FDI) model of the steering system considering its multi-domain components including electric motor, pump, accumulator, hydraulic motor, and transmission; moreover, discrete dynamics of distributor valves are included. Finally, a reconfiguration strategy is developed in order to reconfigure the system according to different faults in the steering system. The developed algorithm is verified through simulation in Matlab/Simulink with different components faults.

Keywords: Mobile robot, Dynamics, Bond graph, FDI, Reconfiguration.

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