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Towards Bond Graph Modeling of a Class of System of Systems: Application to an Intelligent Transportation System

Thesis

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Vers la Modélisation d'une Classe de Système de Systèmes: Application à un Système de Transport Intelligent

Thèse

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par

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In memory of my father

To my mother

Abstract

Large-scale integrated systems working collectively for a common mission are known as Systems of Systems (SoS). In the present work, we propose a modeling method for a class of SoS, namely mechatronic systems, based on the Bond graph modeling approach. The proposed approach is applied to an Intelligent Transportation System (ITS) by modeling the traffic dynamic of Intelligent Autonomous Vehicles (IAVs); where Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communications are considered. Such set of autonomous vehicles describe the organization of a SoS. The traffic dynamic is modeled at three abstraction levels namely: submicroscopic, microscopic, and macroscopic levels. Subsequently, the three levels are combined to develop a *multilevel model of the traffic dynamic* using the same Bond graph approach. The model is simulated for normal and faulty scenarios. Then, the model is validated on a real-time simulator of vehicle dynamics. In addition, real experiments on IAVs are performed to validate the model. Finally, the model is used to develop a supervision strategy for the traffic SoS based on the behavioral and structural analysis of the Bond graph model.

Keywords: System of Systems, Modeling, Intelligent Transportation System, Traffic Dynamic.

Résumé

Les systèmes à grande échelle intégrées qui travaillent ensemble pour une mission commune sont connus sous le nom de Systèmes de Systèmes (SdS). Ce travail propose une méthode de modélisation pour une classe de SdS, à savoir, les systèmes mécatronique, en utilisant lôapproche de Bond graph. Cette approche est appliquée à un Système de Transport Intelligent par la modélisation de la dynamique du trafic de véhicules autonomes intelligent; où les communications de véhicule à véhicule et de véhicule à infrastructure sont considérées. Un tel ensemble de véhicules autonomes décrit l'organisation d'un SdS. La dynamique du trafic est modélisée sur trois niveaux d'abstraction, à savoir: sous-microscopique, microscopique, et macroscopique. Par la suite, les trois niveaux sont combinés pour développer un *modèle multi-niveaux de la dynamique du trafic* en utilisant la même approche du Bond graph. Le modèle est simulé dans des scénarios normaux et défectueux. Ensuite, le modèle est validé sur un simulateur en temps réel de la dynamique du véhicule. En plus, des expériences réelles sur véhicules autonomes intelligent sont effectuées pour valider le modèle. Enfin, le modèle est utilisé pour développer une stratégie de supervision du SdS de trafic basé sur l'analyse comportementale et structurelle du modèle bond graph.

Mots-clés: Système de Systèmes, Modélisation, Système de Transport Intelligent, Dynamique du Trafic.

Acknowledgement

Two people have made this work eminently more feasible than it otherwise might have been: Prof. Rochdi Merzouki and Prof. Belkacem Ould Bouamama with their excellent guidance and constant encouragement. They deserve special thanks and I am eternally grateful to both.

Many thanks go to the European project Weastflows (which provided the context for my work) and the authorities of Interreg IVB North West Europe (NWE) program for funding the project and consequently the entire period of my PhD work.

Special thanks go to my colleagues whose company I have enjoyed, and whose laughs and discussions I have digested. Long discussions in trying to solve the world's problems were characteristic of our interaction and I have learned a great deal as a result of that. The staff members at the laboratory LAGIS also deserve special thanks for their continuous support and help.

I would like to thank Prof. Pushparaj Mani Pathak at IIT Roorkee, India, for his suggestions and encouragement to perform the present work.

An immense sense of gratitude is felt towards my friends all over the world for their love and blessings.

Last but not least, I would like - from the bottom of my heart - to express my sincere gratitude to my family for their unconditional support, love and affection, and for being a great source of inspiration, courage and continuity.

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Acronyms

SE	- Systems Engineering
SoS	- System of Systems
SoSE	- System of Systems Engineering
CS	- Component System
ICT	- Information and Communication Technology
ITS	- Intelligent Transportation System
IAV	- Intelligent Autonomous Vehicle
V2V	- Vehicle to Vehicle
V2I	- Vehicle to Infrastructure
I2I	- Infrastructure to Infrastructure
FDI	- Fault Detection and Isolation
FTC	- Fault Tolerant Control
ARR	- Analytical Redundancy Relation
FSM	- Fault Signature Matrix
SYMBOLS	- **SY**stem **M**odeling by **BO**ndgraph **L**anguage and **S**imulation
LWR	- Lighthill-Whitham-Richards
GHR	- Gazis-Herman-Rothery
OVM	- Optimal Velocity Model
GFM	- Generalized Force Model
FVDM	- Full Velocity Difference Model
IDM	- Intelligent Driver Model
TVDM	- Two Velocity Difference Model
CM	- Centre of Mass

ACRONYMS

1

General Introduction

1.1 Framework of the PhD thesis

This PhD thesis was prepared within the research group *Méthodes et Outils pour la Conception Intégrée de Systèmes* (MOCIS)[1], of the *Laboratoire d'Automatique, Génie Informatique et Signal* (LAGIS)[2]. The laboratory LAGIS is a joint research unit of *Polytech Lille*[3]-*Université de Lille 1*[4], *Ecole Centrale de Lille*[5], and the *Centre National de la Recherche Scientifique* (CNRS)[6]. The LAGIS research objectives concern the development of fundamental, methodological, and technological research in the fields of automatic control, computer engineering and signal processing. The present work was developed under supervision of **Mr. R. Merzouki** (Professor at Polytech Lille - University of Lille 1) and **Mr. B. Ould-Bouamama** (Professor at Polytech Lille - University of Lille 1).

The research group MOCIS is dedicated to research in the field of modeling, structural analysis, control and diagnosis of multi-domain (electrical, mechanical, thermal...) dynamic systems using a unifying tool called **bond graph**. In addition, this research group is involved in developing algorithms for software platforms. The topological organization of the activities of this group is shown in Figure 1.1.

Refer to Figure 1.1; the present work is focused on the bond graph based modeling for supervision purpose of a System of Systems (SoS), and its application

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[1] `http://www.mocis-lagis.fr`

[2] `http://www.lagis.cnrs.fr` (From 1 January 2015, LAGIS is renamed as CRIStAL (cristal.univ-lille.fr))

[3] `http://www.polytech-lille.fr`

[4] `http://www.univ-lille1.fr`

[5] `http://http://www.ec-lille.fr`

[6] `http://http://www.cnrs.fr`

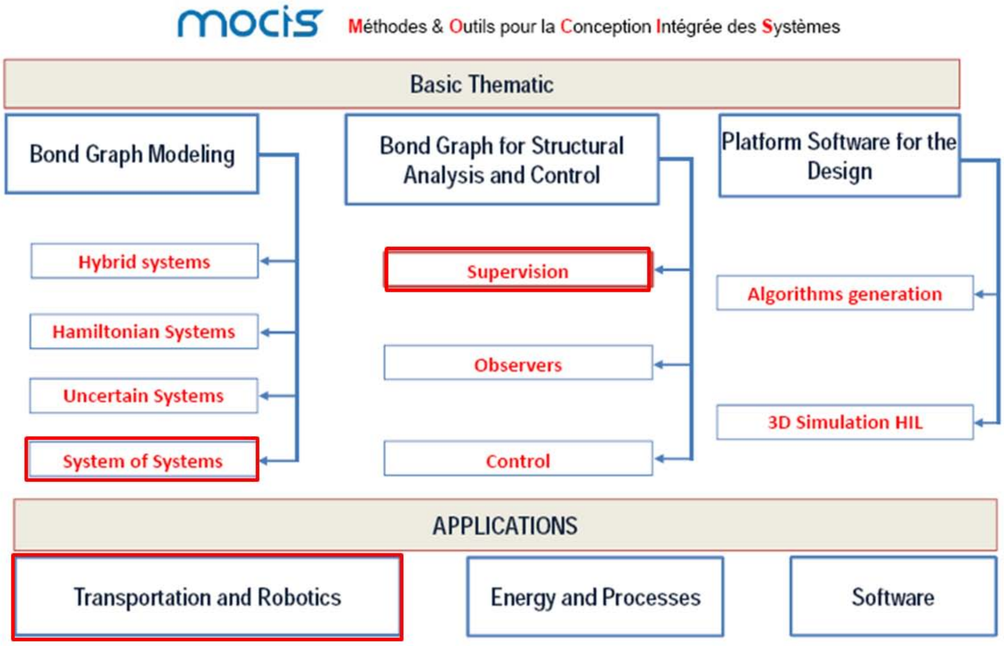

Figure 1.1: Structure of the group MOCIS.

in the field of transportation. Bond graph is an energy-based graphical modeling approach to model in a unified way the physical systems of various natures and independently of the considered domain viz. mechanical, electrical, thermal, etc. This approach allows understanding of the dynamic behavior of a process with the graphical vision. The integrated design of a system exploits specific properties of bond graphs. These properties include (i) causal and structural graphical aspects, (ii) mathematical and physical properties of its behavioral model, and (iii) functional and modular topology. In this context, several research works have been developed within the group including: fault detection and isolation based on the bond graph approach (Ould-Bouamama et al. [2003]); the organizational modeling of a system of systems (Khalil et al. [2012]); and the bond graph modeling of intelligent autonomous vehicles (Merzouki et al. [2013b]).

1.1.1 Project context

The present work was performed in the framework of the European project *Weastflows*[1]. Weastflows is an Interreg IVB *North West Europe* (NWE) project funded by the *European Regional Development Fund* (ERDF) that aims to encourage a shift towards greener freight transport in the NWE region. This project involves 22 partners and 19 observers from countries including France, Germany, Ireland, Luxembourg, the Netherlands, the UK and China.

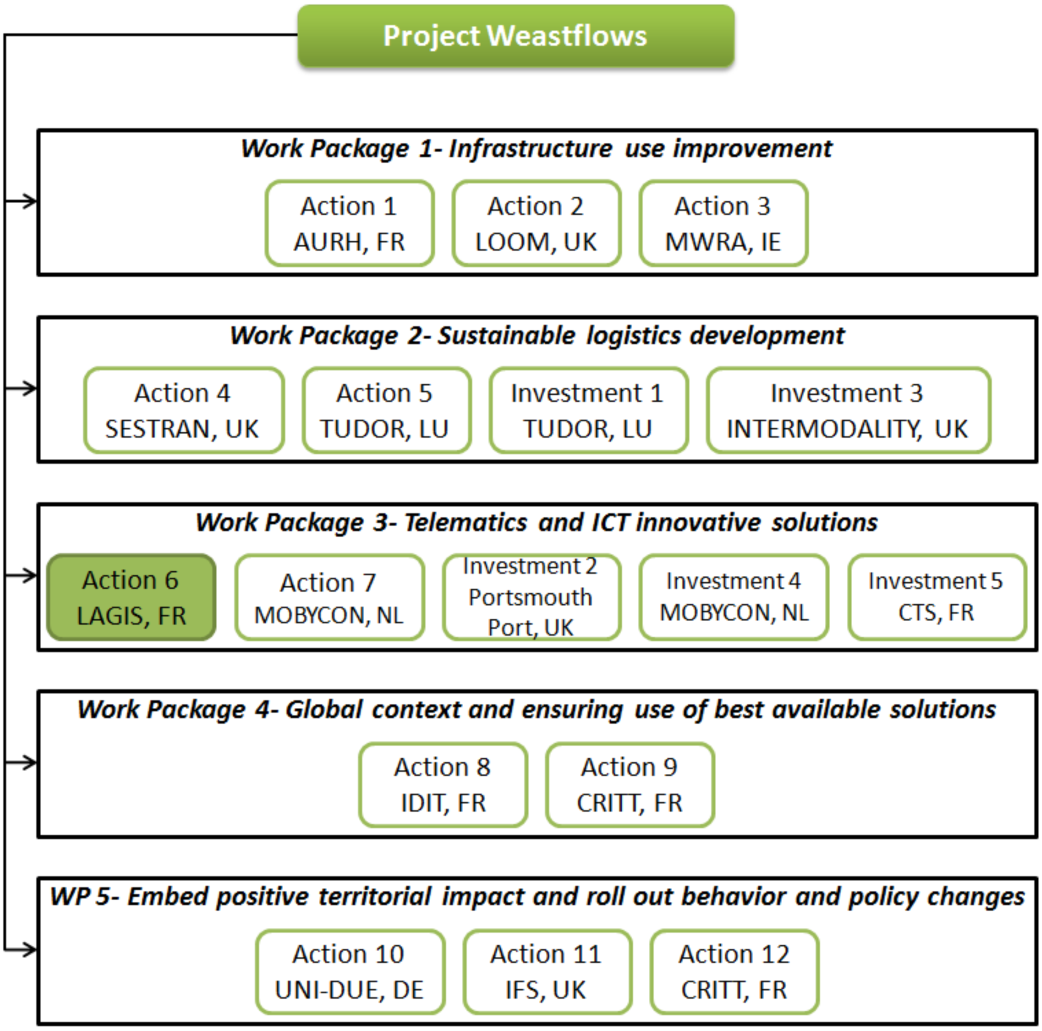

Figure 1.2: Activities of the project Weastflows.

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[1] `http://http://www.weastflows.eu`

Weastflows recognises the importance of developing an efficient freight network within NWE and aims to use ICT technologies to streamline supply chains. The project aims to encourage a move towards more sustainable freight transport to address congestion issues while reducing the environmental impact of freight movements. The project activities are divided in various actions and investments which are grouped in the work packages. In Figure 1.2, the project's actions and investments are given along with their concerned partners.

We are involved in action 6 of the work package 3, which deals with the 'assessment of innovative Information and Communication Technology (ICT) systems' for the sustainable freight transport. In this action, we are assigned to provide four deliverables as follows.

- **First deliverable:** Existing ICT Tools Guide on Private Logistics Organization: State of the Art.
- **Second deliverable:** Existing ICT Tools Report for Public Sustainable Infrastructure Planning and Management.
- **Third deliverable:** ICT Requirements Synthesis.
- **Fourth deliverable:** Knowledge Database on ICT and Telematics Tools.

The summaries of the above deliverables are given in Appendix I.

From the PhD thesis point of view and considering the aim of the project, we extended our work towards modeling of an Intelligent transportation system (ITS) considering the road traffic dynamic in a platoon of Intelligent autonomous vehicles (IAVs). An ITS is a large-scale integrated system and can be modeled like a SoS, which is described in the next section.

1.1.2 Industrial context

An ITS can be defined as the application of advanced information and communication technologies to the transportation system in order to achieve enhanced safety and mobility while reducing the environmental impact of transportation.

In a broad term, ITS can be applied for all modes of transport namely road, rail, water, and air transport. But, generally ITS refers to the road transportation system. According to EU Directive 2010/40/EU (7 July 2010), an ITS is defined as follows.

ITS means systems in which information and communication technologies are applied in the field of road transport, including infrastructure, vehicles and users, and in traffic management and mobility management, as well as for interfaces with other modes of transport.

In the present work, ITS is considered as a road transportation system which includes intelligent autonomous vehicles (IAVs), intellgent infrastructure, and many ICT tools. IAVs communicate with each other to form a platoon using some ICT tools, and the different communications include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and infrastructure-to-infrastructure (I2I). An ITS can play a vital role in industries by providing smooth flow of goods and information among various actors of supply chain.

Having a dynamic model of an ITS allows supervision of the traffic flow and can help in optimizing various freight transport operations. The more benefits of the proposed system can be mentioned as follows.

- This system is very useful in confined space like port environment where space optimization is a critical problem.
- Reduce in emissions because of intelligent electric vehicles.
- Improvement in traffic management with updated information of the traffic flow using ICT.
- Reduce in congestion and jam problems due to intelligent platooning of vehicles.
- Improvement in logistics efficiency due to intelligent vehicles and infrastructure result in fast operations.
- Less human intervention and more safety and security.

Thus, modeling of an ITS helps to achieve the goal of 'sustainable transport' which is the main thematic of the project Weastflows.

1.2 Research problem statement

With the rapid global acceleration especially in the military sector, there was a need for a discipline that focused on the integrated complex systems, and with the rapid advancement in Information and Communication Technologies (ICT) it became possible. These integrated complex systems composed of many operationally independent systems (generally known as component systems (CSs)), which are themselves complex. This class of systems was termed as System of Systems (SoS). The area of study in System Engineering (SE) is well established, but the area of study in SoS is not matured enough yet. How does one extends engineering concepts such as analysis, control, design, modeling, controllability, observability, stability, etc. that can be applied to SoS? Thus, engineering of SoS is challenging and generally known as System of Syestem Engineering (SoSE). We are still attempting to understand its principles, practices, and execution. Unfortunately, there is no universally accepted definition of a SoSE or SoS. Jamshidi [2009a] defined SoS:

Systems of systems are large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal.

Maier [1998] described the five characteristics of a SoS: operational independence of CSs, managerial independence of CSs, geographical distribution of CSs, emergent behavior of SoS, and evolutionary development of SoS. These characteristics enable to differentiate a SoS from the traditional complex system.

SoS has applications in many fields like healthcare, defense, robotics, transportation, space exploration etc. For example, a Boeing 747 airplane, as an element of a SoS, is not SoS, but an airport is a SoS, or a rover on Mars is not a SoS, but a robotic colony (or a robotic swarm) exploring the red planet, or any other place, is a SoS. There are numerous problems and open-ended issues that need a great deal of fundamental advances in theory and verifications (Jamshidi [2009a]).

For another example; an integrated transportation system consists of many entities including: road vehicles, trains, ships, barges, airplanes, roads, railways, canals, container terminals, stations, airports, harbors, ICT tools, transportation equipments, users, service providers, etc., for transporting passengers (passenger transport) and goods (freight transport). This is a large-scale system, which is composed of many complex heterogeneous systems. In a report for the project T-AREA-SoS (Barot et al. [2013]), it is clear that an integrated transport system exhibits characteristics of a SoS, such as the complex nature of the interfaces between systems, the constraints imposed by legacy systems, and the inefficiencies that emerge as the EU27 community evolves. Figure 1.3 shows an example of port terminal SoS.

Figure 1.3: Port terminal SoS.

Refer to example of Figure 1.3, it can be concluded that a SoS is a large-scale system, which is composed of many operationally independent complex systems, called as component systems (CSs). These CSs may be heterogeneous in nature, and composed of different engineering domains (say mechanical, electrical, thermal, etc.). Modeling of such systems is challenging, but very important for supervision and control analysis.

In literature (as described in Chapter 2), it is found that most of the contributions in the area of SoS modeling are based on the organizational modeling approach. The organizational model of a SoS cannot describe the dynamics of the physical CSs within it. Thus, it is difficult to analyze the dynamic behavior of the physical CSs if there are some perturbations. For example, if any of the physical CSs in the considered SoS is faulty then it can stop the SoS to achieve its planned mission. But, if the SoS model consists of dynamic behavioral models of the physical CSs, it is easier to apply control and supervision analysis to recover the SoS from the faulty situations, and to achieve its global mission. In this way, a robust SoS model needs not only the organizational modeling but also the behavioral modeling of the constituent physical CSs. Thus, it is required to have an unified modeling approach for a SoS which can combine the organizational and behavioral modeling approaches.

1.3 Contribution of the thesis

- Proposing a method for the organizational and behavioral modeling of a class of SoS (engineering mechatronic systems) based on the bond graph modeling approach. This is achieved by the dynamic modeling (behavioral modeling) of the physical CSs of a SoS; and then extending the behavioral modeling to the organizational modeling of the considered SoS using the same bond graph approach.

- Applying the proposed SoS modeling approach to an ITS considering the traffic dynamic in a platoon of IAVs; and developing a multilevel bond graph model of the traffic SoS.

- Exploiting the bond graph properties (causal and structural analysis) for supervision of the proposed multilevel model of the traffic SoS. This is achieved by applying the bond graph model-based methods for fault detection, isolation, and reconfiguration on the behavioral models of the physical CSs.

The main contribution of this work is: bond graph ***modeling*** *of a SoS.*

1.4 Publications

Journal paper:

- Kumar, P., Merzouki, R., Conrard, B., Coelen, V., and Ould-Bouamama, B. (2014). Multilevel Modeling of the Traffic Dynamic. *IEEE Transactions on Intelligent Transportation Systems*, 15(3):1066-1082.

Conference papers:

- Kumar, P., Merzouki, R., Conrard, B., and Ould-Bouamama, B. (2014). Multilevel Reconguration Strategy for the System of Systems Engineering: Application to Platoon of Vehicles. In *19th IFAC world congress (IFAC-2014), 24-29 August, 2014. Cape Town, South Africa.*

- Kumar, P., Merzouki, R., Ould-Bouamama, B., and Haffaf, H. (2013). Microscopic Traffic Dynamics and Platoon Control Based on Bond Graph Modeling. In *16th international IEEE conference on intelligent transport systems (IEEE ITSC-2013), 6-9 October 2013, The Hague, Netherlands.*

- Merzouki, R., Conrard, B., Kumar, P., and Coelen, V. (2013). Model Based Tracking Control Using Jerky Behavior in Platoon of Vehicles. In *12th European Control Conference (ECC-2013), 17-19 July 2013, Zurich, Switzerland.*

- Kumar, P., Ould-Bouamama, B., and Haffaf, H. (2012). Communication aspect in ICT for Freight Transport System. In *8th International Conference on Wireless and Mobile Communications (ICWMC-2012), 24-29 June 2012, Venice, Italy.*

1.5 Organization of the thesis

Chapter 1- General Introduction: This chapter explains the context of the thesis. The thesis is performed in the framework of the European project Weastflows, that aims to encourage a shift towards greener freight transport in the NWE region. The chapter describes the role of ITS in achieving the goal of sustainable transport. Furthermore, it is explained that ITS shows the characteristics of a SoS due to its large-scale and complexity of the constituent systems (here, ITS refers to the road transportation only which includes ICTs, intelligent vehicles and infrastructure). Then, the research problem statements are described, where the necessity for modeling a SoS is explained. It is concluded that the modeling of a SoS is challenging, but very important for supervision and control analysis. Finally, the main contribution of the thesis is described, which includes the bond graph-based modeling of a SoS and its application to an ITS.

Chapter 2- State of the Art: This chapter provides a literature review on SoS. Based on the literature review, it is found that the theory and principles of SoS have not been well established yet, and a little contribution is available on SoS modeling. Most of the available models are based on the organizational modeling approach which is not enough to describe the behavior of a SoS. It is required to develop a method of modeling a SoS considering the organizational and the behavioral modeling approaches, while respecting the properties of the SoS. The behavioral modeling describes the dynamics of physical CS, while organizational modeling describes the organization of CSs in a SoS. Thus, it is required to model the dynamic models of the physical CS in order to analyze the behavior of a SoS in faulty status of its CSs. Then, a literature review on road transportation is provided in the chapter, and it is described that the road transportation system can be considered as an application of SoS. A road transportation system, which is composed of intelligent vehicles, intelligent infrastructure, users, and many ICT tools is known as an ITS. Based on the literature review, the traffic flow in road transportation can be modeled at four abstraction levels namely: submicroscopic, microscopic, mesoscopic, and macroscopic modeling. But, there is a lack of a multilevel model of the traffic dynamic which can combine all the levels, from the SoS point of view.

Chapter 3- Bond Graph Modeling of a SoS: In this chapter, a method for modeling of SoS is proposed based on the bond graph modeling approach. First, a brief introduction about bond graph is given, and then a generic multilevel representation of a SoS is described. In this multilevel representation of SoS, the lowest level includes the physical CSs. These physical CSs are operationally and managerially independent, and can complete their respective missions using their own resources. Furthermore, they are dispersed geographically with a continuous exchange of information among them; finally, they exhibit emergent behavior and evolutionary development in the SoS. The higher levels in the SoS include non-physical CSs, which are the organization of CSs at the level lower than their own levels. The properties of a SoS include: operational independence, managerial independence, geographical dispersion, emergent behavior, and evolutionary development. These properties are described mathematically based on bond graph.

Then, the problem statements are explained which highlight the need for behavioral modeling of the physical CSs in a SoS, and it is concluded that if the behavioral models of the physical CSs are not included, then it is difficult to describe the behavior of a SoS in case of some perturbations. Thus, a unified modeling approach called Bond graph is proposed to model the physical CSs, and the approach is described by an example of a mobile robot (Robotino) as a physical CS. The steps for the bond graph modeling, and for the structural and behavioral analysis of the bond graph model are described by modeling Robotino. Then, this approach is extended to the organizational modeling in order to model the higher level CSs. Finally, a multilevel model of a SoS is proposed which combines the behavioral and organizational modeling approaches using a single modeling approach i.e., the bond graph modeling approach.

Chapter 4- Application: Modeling of ITS: In this chapter, the proposed SoS modeling approach is applied to an ITS, considering the traffic dynamic in a platoon of IAVs. A multilevel model of the traffic dynamic of IAVs is developed, which combines submicroscopic, microscopic, and macroscopic level models of the traffic SoS. All the levels of traffic SoS are modeled using the bond graph modeling approach. At the submicroscopic level, the dynamic bond graph model of a four-wheeled electric vehicle is developed and then, at the microscopic level, the car-following model is developed based on virtual interconnection between the submicroscopic models. At the macroscopic level, the macroscopic variables (average speed, density, and flow) are deduced from the submicroscopic and microscopic models. The simulation results show the stick-slip behavior of the interdistance between the IAVs, which represents the driving behavior in a platoon. Finally, the real-time simulation is performed for a platoon of four vehicles using a professional software package, i.e., SCANeR. In addition, the experiments on IAVs are performed to validate the model.

Chapter 5- Application: Supervision of ITS: A multilevel model of the traffic dynamic has been developed in the previous chapter. In this chapter, this model is used for supervision purpose by applying the bond graph-based methods for fault detection and isolation (FDI) on IAVs, considering faults on the wheels. Futhermore, a reconfiguration strategy is proposed at the submicroscopic level for the whole supervision of SoS. In case of a faulty status, FDI enables to detect the faults at the lower level (physical CSs- IAVs) and to evaluate their effects at the higher levels. Then, a model-based reconfiguration strategy is proposed to recover the SoS from the faulty situations, and to continue to achieve its global mission.

2

State of the Art

2.1 System and systems engineering

A system is an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective. The discipline that focuses on the engineering of systems, including complex systems, is known as Systems Engineering (SE). The area of study in SE is well established. As described in DoD [2001], three commonly used definitions of SE are provided by the best known technical standards that apply to this subject are:

i) *A logical sequence of activities and decisions that transforms an operational need into a description of system performance parameters and a preferred system configuration.*[1]

ii) *An interdisciplinary approach that encompasses the entire technical effort, and evolves into and verifies an integrated and life cycle balanced set of system people, products, and process solutions that satisfy customer needs.*[2]

iii) *An interdisciplinary, collaborative approach that derives, evolves, and verifies a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability.*[3]

In summary, systems engineering is an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle balanced set of

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[1] MIL-STD- 499A, Engineering Management, 1 May 1974. Now cancelled.

[2] EIA Standard IS-632, Systems Engineering, December 1994.

[3] IEEE P1220, Standard for Application and Management of the Systems Engineering Process, [Final Draft], 26 September 1994.

system solutions that satisfy customer needs (DoD [2001]). In NASA [1995], simply defined SE as: *a robust approach to the design, creation, and operation of systems.*

2.2 Defining system of systems

There was a trend towards integrated complex systems working collectively for a mission. The proliferation of new Information and Communication Technologies (ICTs) has increased the complexity of the traditional systems, in addition, the integration of these complex systems. That led to the introduction of the concept of System of Systems (SoS). The concept of SoS was introduced in 90s, and there are numerous definitions available for a SoS. Jamshidi [2009a] compiled the following definitions.

- Eisner [1993]- *Systems of systems are large geographically distributed assemblages developed using centrally directed development efforts in which the component systems and their integration are deliberately, and centrally, planned for a particular purpose.*
- Shenhar [1994]- *An array system (system of systems) is a large widespread collection or network of systems functioning together to achieve a common purpose.*
- Manthorpe [1996]- *In relation to joint warfighting, a system of systems is concerned with interoperability and synergism of command, control, computers, communications, and information and intelligence, surveillance, and reconnaissance systems.*
- Kotov [1997]- *Systems of systems are large-scale concurrent and distributed systems that are comprised of complex systems.*
- Maier [1998]- *A system of systems is a set of collaboratively integrated systems that possess two additional properties: operational independence of the components and managerial independence of the components.*

- Lukasik [1998]- *The integration of systems into systems of systems that ultimately contribute to evolution of the social infrastructure.*

- Krygiel [1999]- *A system of systems is a set of different systems so connected or related as to produce results unachievable by the individual systems alone.*

- Pei [2000]- *System of systems integration is a method to pursue development, integration, interoperability, and optimization of systems to enhance performance in future battlefield scenarios.*

- Carlock and Fenton [2001]- *Enterprise system of systems engineering is focused on coupling traditional systems engineering activities with enterprise activities of strategic planning and investment analysis.*

- Sage and Cuppan [2001]- *Systems of systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development (based on Maier's five properties of SoS).*

- DAG [2010]- *SoS is a set of arrangement of independent systems that are related or connected to provide a given capability. The loss of any part of the system will degrade the performance or capabilities of the whole.*

Various definitions of SoS have their own merits, depending on their application. Jamshidi [2009a] defined SoS as follows:

- *Systems of systems are large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal.*

- *System of systems is a 'supersystem' comprised of other elements that themselves are independent complex operational systems and interact among themselves to achieve a common goal. Each element of a SoS achieves well-substantiated goals even if they are detached from the rest of the SoS.*

Based on above definitions, we simply define a SoS as: *A System of systems is a concept which describes an organisation of a large-scale system. It is formed by the integration of many independent component systems, which are networked in the SoS to achieve a common mission.*

No universally accepted definition of a SoS is available at this time (Sage and Biemer [2007]). However, Maier [1998] described the five characteristics to characterize a SoS: operational independence, managerial independence, geographical distribution, emergent behavior, and evolutionary development.

1. **Operational independence of component systems:** This suggests that a system of systems is composed of systems that are independent and useful in their own right, and if a system of systems is disassembled into the constituent systems, these constituent systems are capable of independently performing useful operations by themselves and independently of one another.

2. **Managerial independence of component systems:** This suggests that the component systems generally operate independently to achieve the technological, human, and organizational purposes of the individual organizational unit that operates the system. These component systems are generally individually acquired, serve an independently useful purpose, and often maintain a continuing operational existence that is independent of the larger system of systems.

3. **Geographic distribution of component systems:** Geographic dispersion of the constituent systems in a system of systems is often very large. Often, the individual constituent systems can readily exchange only information and knowledge with one another, and not any substantial quantity of physical mass or energy.

4. **Emergent behavior:** The system of systems performs functions and carries out purposes that may not reside uniquely in any of the individual constituent systems. The principal purposes supporting engineering of these individual systems and the composite system of systems are fulfilled by these emergent behaviors.

5. **Evolutionary and adaptive development:** A system of systems is never fully formed or complete. Development is evolutionary and adaptive over time, and where structures, functions, and purposes are added, removed, and modified as experience of the community with the individual systems and the composite system grows and evolves.

In the present work, the above Maier's five properties will be focused to characterize a SoS. For example, the port terminal system can be seen as a SoS based on the five properties (Figure 2.1).

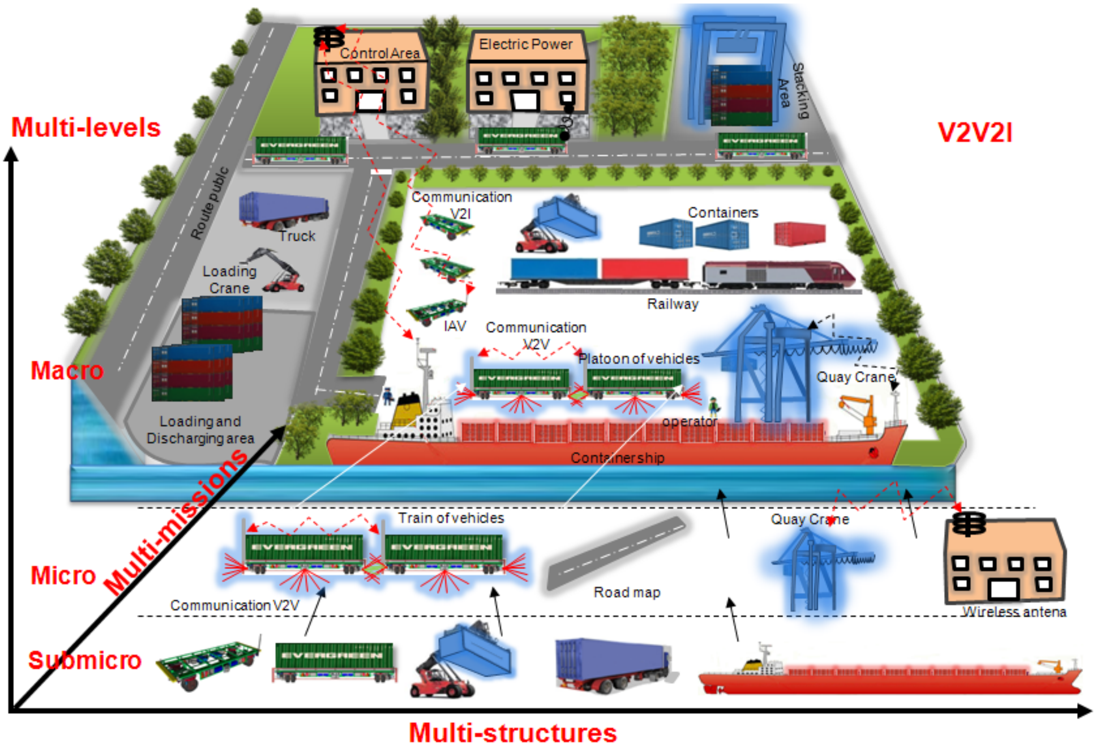


Figure 2.1: Multilevel representation of the port terminal SoS.

Refer to Figure 2.1, it can be observed that the port terminal system is a large-scale system, and can be organized into multilevels of a SoS namely submicro, micro, and macro level. It is composed of many heterogeneous complex systems which represent CSs of a SoS with multi-structures. Each CS is assigned with a mission, and the cooperation of multi-missions results in achieving the global mission of the considered SoS.

The submicro level represents the physical CSs; in this case, the physical CSs include IAVs, loading cranes, trucks, container ships, users, etc. The micro level represents the organizations of submicro level CSs based on communication among them, which include V2V, V2I, and I2I communication. Finally, at the macro level whole SoS can be realized.

In this case, CSs describe an organization of a SoS, because each of them is operationally and managerially independent with their independent missions; they are dispersed geographically with a continuous exchange of information. All the CSs at the submicro and micro levels show emergent behavior by cooperating with each other to achieve the global mission at the macro level; finally, they show evolutionary development by structurally making reconfiguration of their organization.

2.3 System of systems engineering

In the realm of open problems in SoS, just about anywhere one touches, there is an unsolved problem and immense attention is needed by many engineers and scientists. No engineering field is more urgently needed in tackling SoS problems than SE. On top of the list of engineering issues in SoS is the ‘engineering of SoS’, leading to a new field of System of Systems Engineering (SoSE). How can we make structural analysis, control, estimation, stability study, filtering, simulation, etc. on SoS, based on control theory? Among numerous open questions is how such systems can be modeled (Jamshidi [2009a]).

The discipline SE has been well established which concerns about the engineering of complex systems, but, the area of study in the engineering of SoS needs much attention. There was a need for a discipline that focused on the engineering of multiple integrated complex systems (i.e., SoS). Today, this discipline is known as SoSE. Unfortunately, we are still attempting to understand its principles, practices, and execution (Gorod et al. [2008]).

Keating et al. [2003] described several important differences distinguish SE and SoSE as given in Table 2.1.

Although SoSE departs from SE in several significant ways as given in Table 2.1, but SE provides an important foundation in conceptualization and realiza-

Table 2.1: Distinctions between SE and SoSE

Area	**SE**	**SoSE**
Focus	Single complex system	Multiple integrated complex systems
Objective	Optimization	Satisficing
Approach	Process	Methodology
Expectation	Solution	Initial response
Problem	Defined	Emergent
Analysis	Technical dominance	Contextual influence dominance
Goals	Unitary	Pluralistic
Boundaries	Fixed	Fluid

tion (i.e., engineering) of a SoS. Among the strengths of SE that SoSE must draw upon are: (i) the linkage to systems theory and principles for design, analysis, and execution, (ii) interdisciplinary focus in problem solving and system development, (iii) emphasis on disciplined and structured processes to achieve results, and (iv) the iterative approach to develop systems to meet expectations for problem resolution. Drawing on these strengths will only serve to strengthen SoSE development as an evolution of traditional SE. A SoSE can be defined as follows (Keating et al. [2003]).

'The design, deployment, operation, and transformation of metasystems that must function as an integrated complex system to produce desirable results. These metasystems are themselves comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operation, geography, and conceptual frame'.

SoS has applications in many fields like: **defense** (Dahmann [2009]; Dickerson [2009]), **air vehicles** (Wilber [2009]; Colgren [2009]), **robotics** (Sahin [2009]; Sahin et al. [2009]), **space exploration** (Jolly and Muirhead [2009]; Caffall and Michael [2009]), **medical & healthcare** (Wickramasinghe et al. [2009]; Hata et al. [2009]), **environment** (Hipel et al. [2009]; Agusdinata et al. [2009]), **earth observations** (Shibasaki and Pearlman [2009]), **infrastructures** (Thissen and Herder [2009]), **transportation** (DeLaurentis [2009]), **airport operations** (Nahavandi et al. [2009]), **maritime** (Mansouri et al. [2009]), **education** (Lukasik [1998]), **private enterprise** (Carlock and Fenton [2001]), and many more.

The following works describe the contributions over time in the area of SoS/SoSE in terms of characterization, applications, architecture, modeling etc.

- Eisner et al. [1991]: described the role of computer tools to develop the discipline SoSE.
- Maier [1998]: provided important contribution in the field of SoS, and proposed definition, taxonomy and a basic set of architecting principles to assist in design of a SoS.
- Sage and Cuppan [2001]: provided detail study on Systems, SoS, and federation of systems (FoS). In addition, engineering and management of SoS and FoS are described with emphasis on defense system. **Application:** defense.
- Keating et al. [2003]: described the issues in SoSE with a detailed literature review. Current and future perspectives of SoSE are provided, with implication for design, deployment, operation and transformation of SoS.
- Bar-Yam et al. [2004]: presented some additional characteristics of SoS that should be included in a more comprehensive and generalized definition and highlighted some issues in characterization of a SoS. From analysis they concluded that these following characteristics were common across the three fields of biology, sociology and military: Evolutionary development, emergent behavior, self organization, adaptation, complex systems, individual specialization, and synergy; but other properties may not be satisfied. **Application:** biology, sociology, and military.
- DeLaurentis et al. [2004]: explained the SoS perspectives in decision making, and exemplified by the next generation transportation system. **Application:** transportation.
- Boardman and Sauser [2006]: described the five distinguished characteristics for a SoS namely; autonomy, belonging, connectivity, diversity, and emergence. It is explained that both system and SoS consist of parts, relationships and a whole that is greater than the sum of the parts, but these terms differ in a fundamental sense, one that impacts their structure, behavior and realization, and the distinction comes from the manner in which parts and relationships are gathered together and therefore in the nature of the emergent whole.

- Sahin et al. [2007]: presented a simulation framework for SoS architectures. The application of extensible markup language (XML) is described to represent data communicated among heterogeneous constituent systems of a SoS.

- Simpson and Dagli [2008]: analyzed characteristics and attributes of systems and SoS. The following key system attributes and characteristics have been identified as essential components of successful systems: flexibility, adaptability, modular design, open interfaces, and contextual awareness as well as local system control over connection to global SoS resources.

- Gorod et al. [2008]: provided a detailed literature review on SoS, and described the management framework for SoSE. A case study is provided to illustrate how the proposed framework could be applied. **Application:** integrated deepwater system.

- DeLaurentis [2008]: described the modeling and analysis of a SoS. Taxonomy is identified to model road transportation, air transportation and space transportation. **Application:** transportation.

- Jamshidi [2009a]; Jamshidi [2009b]: introduced two books dedicated to SoS. The books covered a wide variety of SoS topics including principles, architecture, applications etc.

- Mahulkar et al. [2009]: described agent-based modeling for a SoS. The SoS approach is applied for modeling and simulation of a ship environment with wireless and intelligent maintenance technologies. **Application:** navy warfighters.

- Mansouri et al. [2009]: proposed a framework to engineer and manage maritime transportation systems from a SoSE perspective. **Application:** maritime.

- Baldwin and Sauser [2009]: described a theoretical model using set theory to define five characteristics of a SoS: autonomy, belonging, connectivity, diversity, and emergence. In addition, agent-based modeling and simulation is described for a SoS.

- DiMario et al. [2009]: described the SoS collaborative formation, and performed a case study on autonomous systems.

- Sauser et al. [2010]: described an approach to provide insight of a SoS. A foundation is established to understand the behavior of SoS by deeper analysis of their structures using biological analogies. **Application:** biology.

- Ender et al. [2010]: proposed a modeling and simulation framework that supports architecture level analysis of Ballistic Missile Defense System (BMDS), including neural network based surrogate model. **Application:** defense.

- Dauby and Upholzer [2011]: described an approach utilizing computational intelligence, agent-based modeling, and wireless ad hoc network simulation as a computational test bed for exploring the generalized dynamics of complex adaptive systems. It is proposed that the evolutionary algorithm and agent-based model provide the flexibility and autonomy needed to simulate a representative SoS.

- Cooksey and Mavris [2011]: proposed game theory approach for modeling a SoS. The proposed approach is used to model smart power grid. **Application:** smart grid.

- Liu [2011]: proposed the design of an emergency management system based on the characteristics of SoS. **Application:** emergency management.

- Mostafavi et al. [2011]: proposed analysis of system of innovation (SoI) based on the SoS approach.

- Zhou et al. [2011]: discussed the issues in SoSE. The existing methods for modeling SoS are reviewed, and a computational method for SoS modeling is proposed which could be applied to future production system.

- Gezgin et al. [2012]: described a modeling approach for SoS in a safety critical context considering its evolutionary nature, and focused on the ability to reconfigure the SoS in case of changes of the environment or the SoS itself. **Application:** fire fighting system.

- Khalil et al. [2012]: proposed a graphical modeling approach for a SoS based on hypergraphs. The architectural representation of hypergraphs is used for model-based supervision of SoS. **Application:** intelligent transportation system.

- Darabi and Mansouri [2013]: modeled competition and collaboration among constituent elements of a SoS to observe the impact on autonomy and belongingness. **Application:** swarm of robots.

- Ge et al. [2014]: proposed executable modeling of a SoS from architectural data. **Application:** air interdiction.

In the literature, a little contribution is available on modeling of SoS. Because SoS has been introduced for various application domains, dedicated tools have been developed to model and operate them. Nevertheless, until recently, SoS remained a theoretical concept with no generic simulation formalism. Several modeling approaches of SoS are non-generic and focus on domain related issues.

For modeling of SoS, data-based methods or model-based methods can be applied, both the approaches have some advantages and disadvantages. In the present work, we focus only on the model-based approach because it is easier to apply control and supervision on a model. Some of the existing approaches in literature for modeling of SoS include; agent-based modeling (Mahulkar et al. [2009]; Zhou et al. [2011]; Gezgin et al. [2012]; Soyez [2013]), set theory (Baldwin and Sauser [2009]), game theory (Cooksey and Mavris [2011]), and hypergraph (Khalil et al. [2012]).

The graphical approaches are suitable for modeling complex systems due to ease of implementation and interpretation. In addition, the architectural representation of a graph-based model enables to apply supervision strategy. The graph-based approaches are often applied for systems considered as independent entities. These approaches are able to model only binary relations, however, they do not support interconnections of different systems. But in a SoS, there may be many interconnections among different systems. For example, the representation of many connected systems inside a node is difficult to model in a graph.

Khalil et al. [2012] represented the interconnections of SoS using a specific graphical formalism of the hypergraphs. A hypergraph is the generalization of a graph, where an edge can connect any number of vertices, the edge is termed as hyperedge. The hyperedge can include all the vertices of the hypergraph, and a vertex should belong to at least one hyperedge (Figure 2.2).

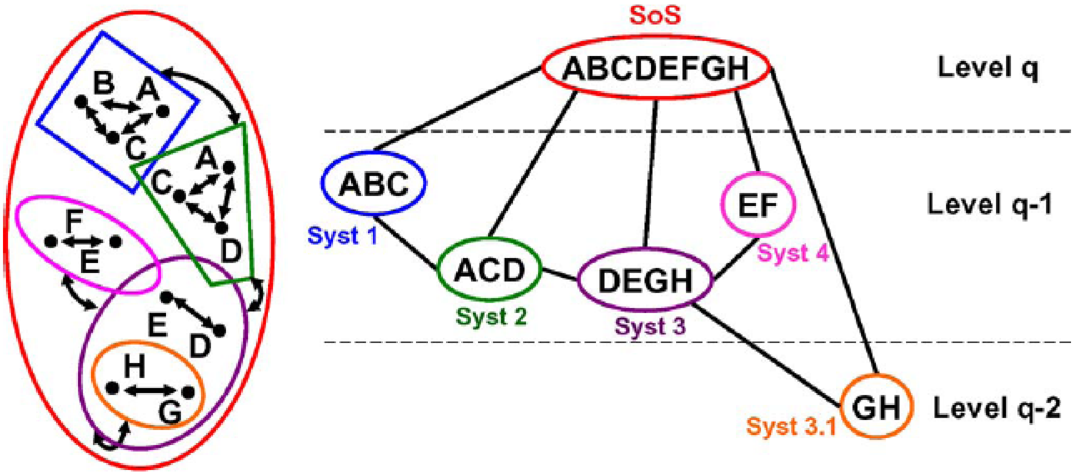


Figure 2.2: SoS hypergraph (left) and its graphical representation (right). (source: Khalil et al. [2012])

Refer to Figure 2.2, it can be seen in the hierarchical graphical representation of the SoS that different systems (Syst1, Syst2,...) are formed based on the interconnection between different nodes (A, B, C,...). These systems can be represented by an hyperedge, for example, Syst1 is represented by the hyperedge-ABC. The nodes (A, B, C,...) represent the physical systems in the SoS.

In the above hypergraph approach (and also other approaches including agent-based model, set theory, and game theory), the dynamic models of the physical systems are not included, and the behaviors of the physical systems cannot be analyzed. In addition, there is absence of theoretical methods to apply structural analysis on hypergraph. Based on the literature review, we can position our work as shown in Figure 2.3.

In Figure 2.3, three research areas are shown for SoS namely; concept, modeling, and application. In concept part, many researchers have contributed to develop principles and charactrization of SoS. Furthermore, many researchers have

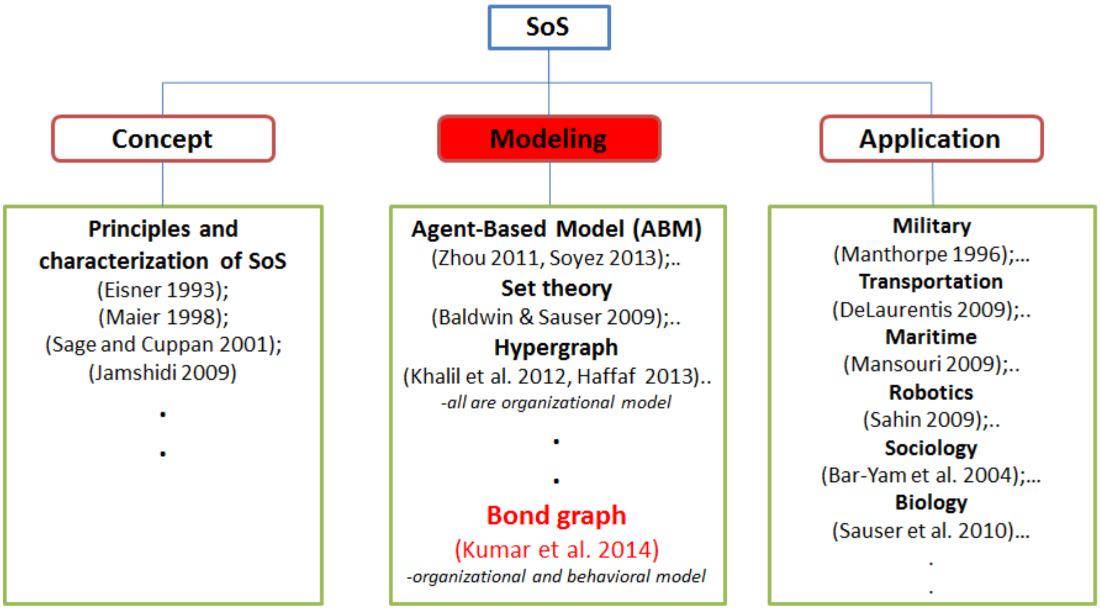


Figure 2.3: Main contribution of the present work.

dedicated their research for different applications of SoS. In the present work, we focus on the modeling of SoS. Most of the existing models of SoS are based on the organizational modeling approach and the behavioral models of the physical component systems are not considered, these existing modeling approaches include agent-based model, set theory, game theory, and hypergraph. Thus, the main contribution of this work is to propose a modeling method for a SoS, which includes the behavioral and the organizational modeling approaches. A unified modeling approach is proposed based on Bond graph for multilevel modeling of a SoS.

2.4 Transportation as SoS

The SoS approach can be applied in the field of transportation. DeLaurentis (DeLaurentis [2005]; DeLaurentis et al. [2004]; DeLaurentis [2008]) described that the transportation system can be considered as an application of a SoS based on its characteristics, complexity, and large-scale. Moreover, the different modes of transportation (road, rail, water, and air transport) can be considered as a separate SoS due to their complexities.

Transportation system can be defined as: *A facility consisting of the means and equipment necessary for the movement of passengers or goods.*

At its most basic, the term *'transportation system' is used to refer to the equipment and logistics of transporting passengers and goods. It covers movement by all forms of transport, from cars and buses to boats, aircraft and even space travel.*

In this way, a transportation system consists of many entities (road vehicles, trains, ships, barges, airplanes, roads, railways, canals, container terminals, stations, airports, harbors, ICT tools, transportation equipments, users, service providers, etc.) for transporting passengers (passenger transport) and goods (freight transport).

Based on the mode of transport to move goods/passengers from a point of origin to a destination, the transportation system can be classified into four modes of transportation (Figure 2.4):

- Road transportation
- Rail transportation
- Water transportation
- Air transportation

Refer to Figure 2.4, in the present work, we focus on the road transportation. When the entities of the road transportation are integrated with Information and Communication Technologies (ICTs), the transportation is known as Intelligent Transportation System (ITS). Here, ITS is referred to the road transportation only, which consists of Intelligent Autonomous Vehicles (IAVs), intelligent infrastructures, embedded hardware and software equipments, users, etc. The communication occurs among these entities based on some ICT tools, and the different communications include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and infrastructure-to-infrastructure (I2I).

In the present work, ITS is considered for the traffic of IAVs. The traffic dynamic in a platoon of IAVs can be modeled at various levels of a SoS. The IAVs represent the physical CSs of the considered SoS, because they are operationally

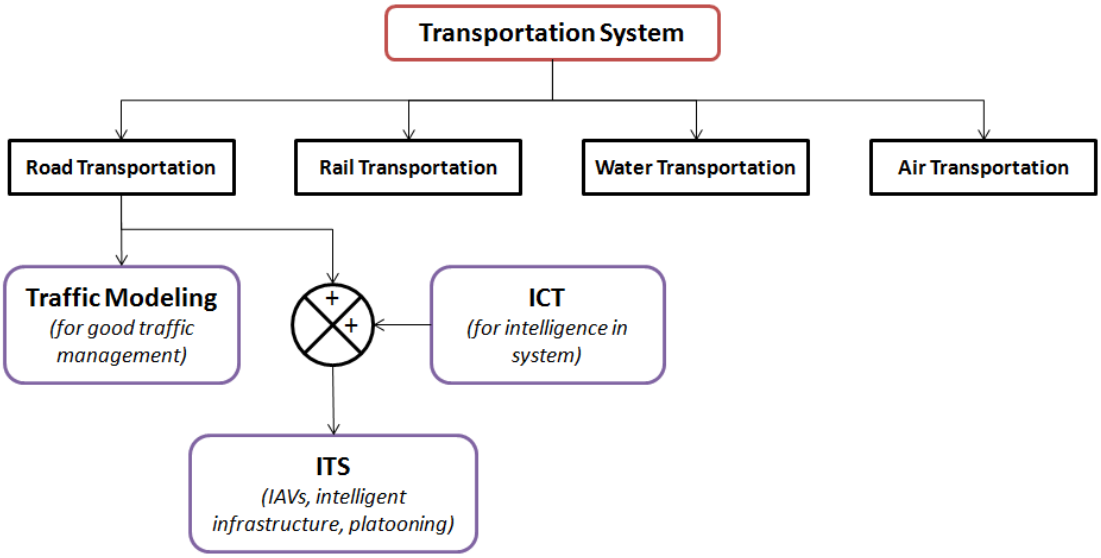


Figure 2.4: Transportation system and its different modes of transport.

and managerially independent. Furthermore, they are geographically dispersed, with a continuous exchange of information (V2V communication) among them. The organization of IAVs represents the CSs at the higher levels; finally they can structurally make a self-reconfiguration of their organization to achieve the global mission of the SoS.

Road transport is the most used mode of transport, and is the major cause of emissions compared to other modes of transport (rail, water, and air transport). In EU-27, road transport accounts for approximately 70% of all transport related CO2 emissions (Psaraki et al. [2012]). Thus, management of the road traffic flow is important in order to minimize adverse effects on environment.

Traffic management enables to achieve good traffic conditions on roads, which leads to decrease in the cost of transport, pollution, accidents, and travel time. Traffic management requires a clear understanding of the traffic flow operations, which can be achieved by the traffic modeling and analysis. In this way, it can be concluded that modeling of the traffic flow is required for sustainable transportation.

2.4.1 Traffic flow modeling

The traffic system is a system of several vehicles (in ITS, vehicles are IAVs) communicating with each other. IAVs represent the physical CSs of the traffic SoS (Figure 2.5).

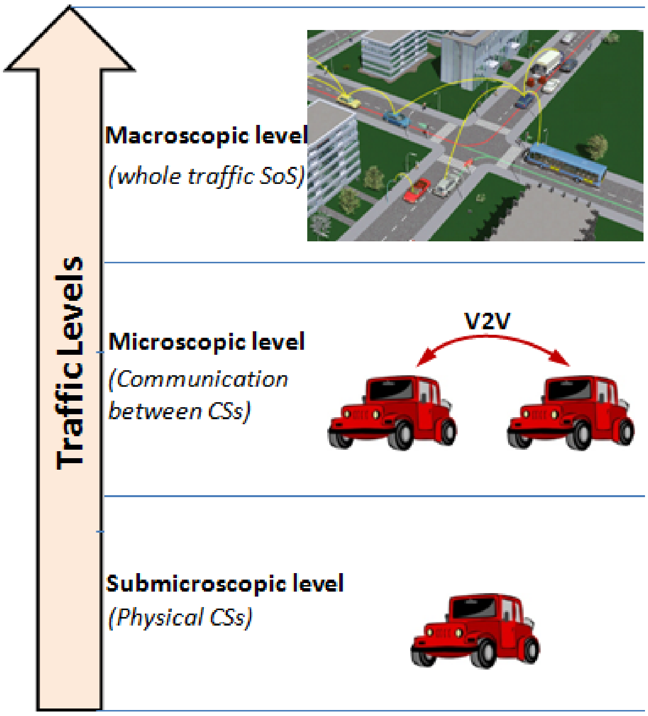


Figure 2.5: Multilevel representation of the traffic SoS.

Refer to Figure 2.5, the traffic system can be modeled as a multilevel SoS, here we consider three levels to represent the traffic SoS namely submicroscopic, microscopic, and macroscopic level. The submicroscopic level represents the physical CSs (IAVs); the microscopic level represents the organization of the physical CSs based on V2V communication; and the macroscopic level represents the whole traffic SoS.

Based on the level of details, the traffic models may be categorized into four types: submicroscopic, microscopic, mesoscopic, and macroscopic level models (Figure 2.6). In the present work, we do not consider the mesoscopic level modeling, but for the completeness of the literature review on traffic modeling, the mesoscopic level models are also described.

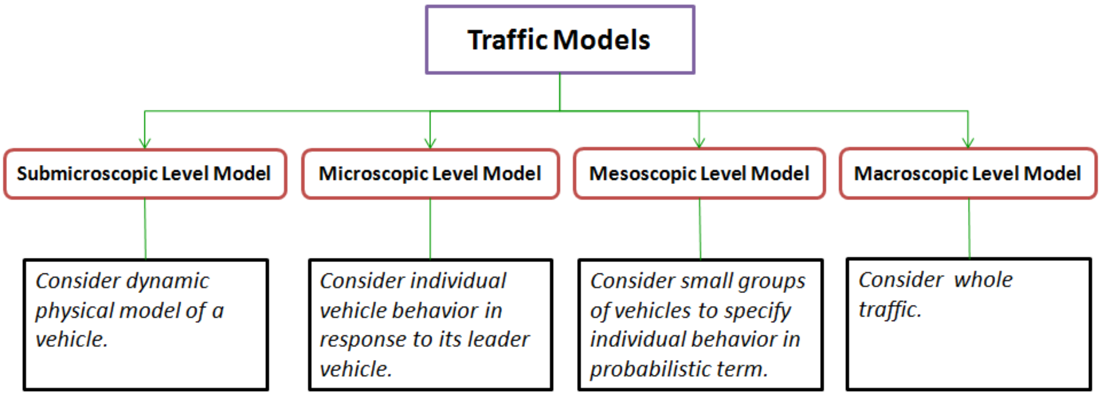


Figure 2.6: Types of traffic models.

Submicroscopic models describe the dynamics of a vehicle, such as the longitudinal, lateral, and actuator dynamics of the vehicle. Microscopic models describe both the space-time behavior of the system's entities (i.e., vehicles and drivers) and their interactions at a high level of detail (individually). These models are based on supposed mechanisms describing the process of one vehicle following another. The follower vehicle's motion (position, speed, and acceleration) is determined according to the motion of the leader vehicle. Mesoscopic models describe traffic at a medium detail level. Vehicles' and drivers' behaviors are not distinguished nor described individually, but their individual behavior is specified by means of probability distribution functions. Macroscopic models describe traffic as a fluid flow without distinguishing its constituent parts. Therefore, traffic is represented by taking into consideration the average values of traffic stream characteristics (mean speed, flow, and density), which provide low level of detail.

A. Macroscopic models

The research in the traffic flow modeling began in the 1930s, with the pioneering studies conducted by Greenshields et al. [1935]; based on the data collected, he suggested a linear speed-density relation:

$$v = v_f \left(1 - \frac{\rho}{\rho_j}\right) \tag{2.1}$$

where, v_f and ρ_j are free speed (m/s) and jam density (vehicles/m) respectively. The other relations for speed-flow and flow-density can be obtained by applying the fundamental relation. The fundamental relation relates the main parameters of traffic flow, namely, density ρ (vehicles per unit distance), flow q (vehicles per unit time) and speed v (distance per unit time), as given in

$$q\left(x,t\right)=\rho(x,t).v(x,t) \tag{2.2}$$

The model is simple and requires only two parameters: free speed and jam density. This model assumes linear relationship between speed and density but hardly in real situation. So, the model provides a rough simplification of traffic behavior.

Lighthill and Whitham [1955] and Richards [1956] independently proposed a simple continuum model to describe the characteristics of traffic flow now known as the Lighthill-Whitham-Richards (LWR) model. The LWR model is one of the well known continuum traffic flow models in literature. The key postulate of the LWR model was that there exists some functional relation between the flow and the density, mathematically:

$$q\left(x,t\right)=f\left(\rho\left(x,t\right)\right) \tag{2.3}$$

In this model, a traffic stream model (relationship between the traffic state variables of flow, speed and density) is supplemented by the fundamental relation as given in (2.2), which expresses the average speed of all vehicles on the road, and the conservation equation (continuity equation) of vehicles. This is the well established rule in traffic flow theory, and all the traffic flow models must satisfy the law of conservation of number of vehicles as follows.

$$\frac{\partial\rho\left(x,t\right)}{\partial t}+\frac{\partial q\left(x,t\right)}{\partial x}=0 \tag{2.4}$$

The LWR model is a first-order robust, simple, and anisotropic model (Zhang [2002]) based on fluid dynamics, but it has some shortcomings such as being inaccurate for light traffic condition and failing to model stop-and-go and vehicle clustering phenomena. Many researchers represented the extension of the LWR model. Lebacque [2003] proposed a two-phase model, which recaptures the most essential properties of the LWR model and takes into account the fact that acceleration must stay bounded. Logghe and Immers [2008] proposed a multiclass extension of the LWR model, and Jin [2010] presented a model for lane-changing traffic dynamics. In 1971, Payne [1971] proposed a second-order model of traffic flow, and Zhang [2002] also presented an improved second-order model. Kotsialos et al. [2002] described the macroscopic traffic simulator METANET, which is based on a second-order traffic flow model.

Kerner introduced the three-phase traffic theory and presented significant work on the theory of congested traffic flow (Kerner [2002, 2004, 2005]). Vandaele et al. [2000] presented a traffic flow model that is based on queueing theory. Herman and Prigogine [1979] developed a two-fluid model to describe the average operating performance of urban traffic and Xiang et al. [2007] described the sampling strategies on data collection for practical application of the two-fluid model in an urban area.

In 2005, Lozano et al. [2005] proposed the macroscopic model of traffic flow using bond graph. The model is based on the fluid dynamics. In addition, Abouaissa et al. [2006], Iordanova et al. [2006], Benmansour et al. [2006], and Prasanna et al. [2009] used bond graph to model the traffic flow analogous to the fluid flow.

B. Mesoscopic models

Generally, mesoscopic models are derived in analogy to gas-kinetic theory. Prigogine and Herman [1971] were the first to describe the dynamics of traffic flow by using a so-called gas-kinetic approach, whereas Paveri-Fontana [1975] presented an improved gas-kinetic model. Helbing [1997] presented a gas-kinetic model for multilane traffic flow operations. Hoogendoorn and Bovy [2001] consolidated the various gas-kinetic traffic flow models presented by Prigogine, Paveri-Fontana, and Helbing.

In the present work, we are not considering the mesoscopic level traffic modeling.

C. Microscopic models

Microscopic models are also called 'Car-following' models, in which the leader vehicle influences the driving behavior of the follower vehicle. Various car-following models have been developed since the early 1950s. In 1953, Pipes [1953] developed safe-distance car-following models describe the dynamics of a vehicle in relation to its leading vehicle. Pipes model is given as follows.

$$d_m = b + L_n + 1.023 v_{n+1} \tag{2.5}$$

where, d_m is minimum safe distance headway (m), v_{n+1} is the speed of the follower vehicle (m/s), b is the prescribed legal distance when vehicles are standstill, and L_n is the length of the leader vehicle. Other safe-distance models are also presented in the following contributions. Forbes et al. [1958] presented an improved safe-distance model taking into consideration the driver reaction time. A similar approach was proposed by Kometani and Sasaki [1959] through the manipulation of the basic Newtonian equations of motion. The model assumed that vehicle separation is proportional to the speed of both the subject vehicle and the leading vehicle. Gipps [1981] derived the model by setting the limits of performance of the driver in terms of not exceeding the desired maximum speed and the vehicle in terms of not exceeding its maximum acceleration/deceleration capabilities.

In 1961, Gazis et al. [1961] proposed a generic stimulus-response model. The model is known as the Gazis-Herman-Rothery (GHR) model. The GHR model is the most wellknown model in traffic literature. The stimulusŰresponse models assume that the response of a driver depends on the driver sensitivity and the stimulus. The models describe the acceleration and deceleration response of a follower vehicle from the driving action of the leader vehicle. Mathematically

$$a_{n+1}(t+\tau) = c \frac{v_{n+1}^{m}(t+\tau)}{\left[x_n(t) - x_{n+1}(t)\right]^{l}} \left[v_n(t) - v_{n+1}(t)\right] \tag{2.6}$$

where, x, v and a are position (m), speed (m/s) and acceleration (m/s^2), respectively; and subscripts n and $n+1$ represent the leader and follower vehicles, respectively. The symbols t and τ represent the time and the reaction time, respectively; while m, l, and c are constants parameters to be determined (Brackstone and McDonald [1999]).

Another car-following model, which is known as the optimal velocity model (OVM), was proposed by Bando et al. [1995]. In this model, the legal velocity function is introduced, which is a function of the distance headway between the leader and follower vehicles. In addition, some other improved car-following models were described in the following contributions. Helbing and Tilch [1998] developed an improved model to cope with the problems of too high acceleration and unrealistic deceleration with OVM, which is known as generalized force model (GFM). Jiang et al. [2001] proposed a model that partly settled the problems in OVM and GFM. Since the model takes both positive and negative velocity differences into account, it is called the full velocity difference model (FVDM).

Treiber et al. [2000] proposed the intelligent driver model (IDM). Kesting and Treiber [2008] calibrated IDM and FVDM and found that IDM shows a higher degree of agreement than FVDM. Li and Li-qun [2008] presented a modified OVM by adding an acceleration-adjustment term. In addition, Ge et al. [2008] developed a two velocity difference model (TVDM) and the results reveal that unrealistically high deceleration will not appear in TVDM. Jin et al. [2010] proposed the extended non-lane-based car-following model undertaking lateral separation into account. Peng et al. [2011] presented a new optimal velocity difference model based on the FVDM, which solves the problem of the unrealistically high deceleration in FVDM. Zheng et al. [2012] proposed a two-lane visual angle car-following model, which is based on OVM and FVDM, and analyzed the influence of lateral discomfort using the model.

Michaels [1963] proposed a psychophysical car-following model, and Wiedemann [1974] defined thresholds to describe different regimes in the car-following model. Nagel and Schreckenberg [1992] introduced the cellular automata model. There exist traffic simulation packages for car-following models. Bham and Benekohal [2004] described the software packages CELLSIM for traffic simulation based on cellular automata model. The software package AIMSUN is based on the safety distance model, MITSUM is based on the GHR model, and VISSIM is based on the psychophysical model (Olstam and Tapani [2004]).

Some contributions in vehicles platoon control are following. Yi and Chong [2005] proposed an impedance control system for a vehicle platoon system. Avanzini et al. [2009] proposed a global platoon control strategy, supported by inter-vehicle communications. Contet et al. [2011] proposed a local control approach to linear platoons for the control of inter-vehicle distance and common trajectory matching.

D. Submicroscopic models

At the submicroscopic level, the vehicle dynamics are presented in response to acceleration, braking, steering, etc. (Tampere and Arem [2001]). Some of the contributions on modeling of the vehicle dynamics are as follow. Pacejka [1985] explained the bond graph technique for modeling complex vehicle systems. Drozdz and Pacejka [1991] established the 2-D and 3-D models of a vehicle to analyze the handling response of the steering. Hrovat and Tobler [1991] developed the bond graph model of automotive power trains. Margolis and Shim [2001] developed a 3-D bond graph model of a four-wheel nonlinear vehicle dynamic model that is useful for controller development.

Pathak et al. [2008] developed the 2-D bond graph model of an autonomous vehicle for reconfiguration of directional handling, whereas Sandoval [2008] explained the lateral vehicle dynamics using bond graph. Bera et al. [2011] developed a 3-D bond graph model of a four-wheeled vehicle to evaluate the antilock braking system. Loureiro et al. [2012] developed a 2-D bond graph model of a four-wheeled autonomous vehicle for structural diagnosability and recoverability. Cipek et al. [2013] developed a bond graph model of a two-mode power-split hybrid electric vehicle for the purpose of dynamics analysis and control.

2.5 Conclusion of the literature review

A. Literature on SoS

- A SoS is a large-scale integrated system, and composed of independent heterogeneous systems which are complex themselves. In addition, a SoS exhibits specific properties (operational and managerial independence, geographical dispersion, emergent behavior, and evolutionary development) which differentiate it from the traditional complex systems.

- Theory and principles of SoS have not been well established yet, thus, the engineering of SoS (modeling, analysis, controllability, observability, etc.) is a challenge for the engineers and the researchers. There is a need of advancement in the discipline known as SoSE.
- Based on the literature review, it can be concluded that a little contribution is available in the literature on SoS modeling.
- Most of the available models are based on the organizational modeling approach which are not enough to describe the behavior of a SoS, and it is difficult to apply the control and supervision analysis.
- Thus, it is required to develop a method of modeling for a SoS considering the organizational and the behavioral modeling approaches, while respecting the properties of the SoS.

B. Literature on Transportation

- Transportation system can be considered as an application of SoS, due to its large-scale and complexity of the constituent systems.
- The road traffic flow models are based on submicroscopic, microscopic, mesoscopic, and macroscopic modeling approaches, which provide very high, high, medium, and low levels of details of the traffic flow, respectively. But, there is lack of a model which can combine all the modeling approaches.
- In the literature, the existing traffic models are based on submicroscopic, microscopic, or macroscopic level modeling, but a multilevel model is not considered which can combine all the levels; while from SoS point of view, it is important to consider all the levels of modeling for the purpose of supervision. For this reason, a unified modeling tool for all the levels could be the best solution for the traffic management as a SoS.

3

Bond Graph Modeling of a SoS

3.1 Introduction

A SoS is an integrated large-scale system, which is composed of many complex, heterogeneous, and independent operable systems. Precisely, SoS can be defined as: *Systems of systems are large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal.* (Jamshidi [2009a]). Modeling of such systems is challenging because of their large-scale, and complexity of the heterogeneous CSs. In addition, the discipline of SoSE is not well developed.

Based on the literature review on SoS in the previous chapter, it can be concluded that there are not much works available related to the modeling of SoS. Most of the available models are the organizational models which don't consider the dynamic behavioral models of the physical CSs in a SoS. The behavioral model of the physical CSs enables to apply control and supervision strategies.

In this chapter, a generic multilevel model of a SoS is developed using a unified modeling approach called bond graph. First, a brief introduction about the bond graph modeling approach is given. Then, a multilevel representation of a SoS is developed based on hierarchical approach. The properties of a SoS are described based on bond graph. Finally, a methodology is described to develop a unified multilevel bond graph model of a SoS, which includes the behavioral and organizational modeling approaches.

3.2 Bond graph modeling

The bond graph modeling approach was invented by H. M. Paynter in 1959 (Paynter [1961]). This approach for modeling mechatronic systems is well developed in the literature. The bond graph is not only a powerful modeling and simulation tool of mechatronic systems, but also allows control and diagnosis analysis. As shown in Figure 3.1, the dynamic bond graph model deduced directly from the physical mechatronic system is used not only for simulation (using any software tool), but also for diagnosability, controllability, and observability analysis; and sensor placement (Merzouki et al. [2012]).

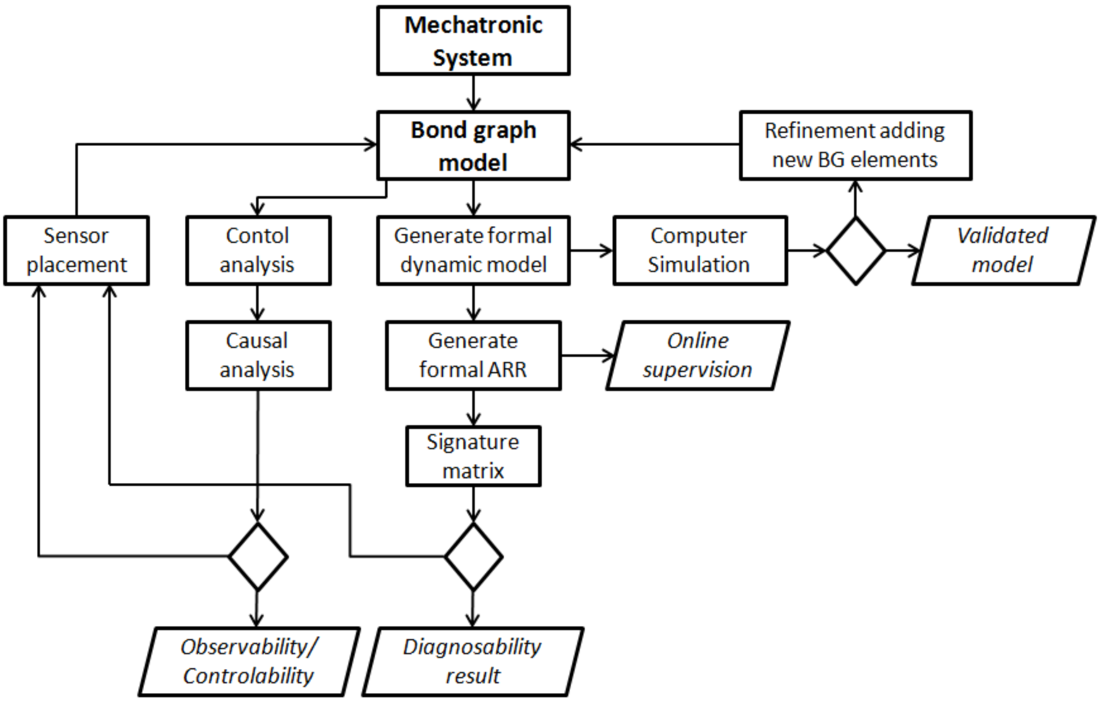


Figure 3.1: Bond graph modeling for control and diagnosis design. (source: Merzouki et al. [2012])

Bond graph is based on the power exchange phenomena between systems of various domain. It can be denoted as $G(N; E)$, where N is a set of nodes which represent the physical systems, and E is a set of edges which represent the power/information bonds between nodes.

Refer to Figure 3.2, S_1 and S_2 are two physical systems (these systems can be multi-domain systems) which represent nodes, and the half-headed arrow is a

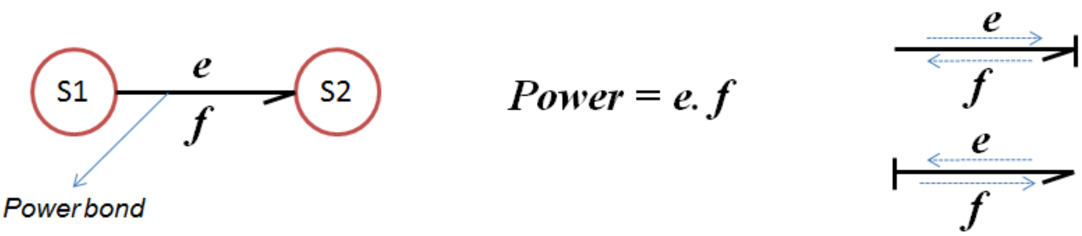


Figure 3.2: Bond graph modeling of power exchange between systems.

power bond which represents an edge of $G(N;E)$. This power bonds describes the power exchange between the physical systems based on two unified power variables namely effort (e) and flow (f). The power in a power bond can be calculated by the multiplication of its power variable e and f. The direction of effort in a bond is represented by putting a stroke on the arrow; the other side of the arrow (without stroke) represents the direction of flow. This stroke on a bond, called 'causal stroke', indicates how the information flow path for variables e and f are simultaneously determined on a causalled bond. Thus, the notion of causality describes a series of cause and effect to decide the order in which the variables are to be computed.

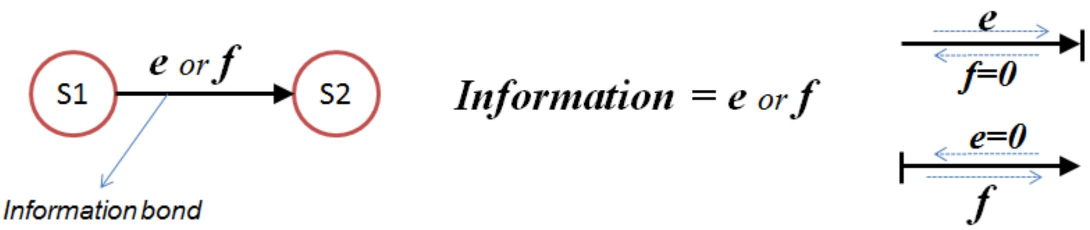


Figure 3.3: Bond graph modeling of information exchange between systems.

Refer to Figure 3.3, S_1 and S_2 are any physical systems which exchange only information, and there is no exchange of energy between them. This information exchange is modeled using information bond in bond graph, which is represented by a full-headed arrow. This information bond carries either effort information e (effort activated bond with zero flow) or flow information f (flow activated bond with zero effort).

Any physical system - of any domain viz. electrical, mechanical, thermal, etc. - can be modeled using the following unified bond graph elements: (i) active elements (sources of effort Se and flow Sf) which provide input power to the system, (ii) passive elements transform input power into dissipated (resistive element R) and stored (capacitance C and inertia I elements) energies, (iii) power conserving elements (flow conservation junction '0', effort conservation junction '1', transformer TF , and gyrator GY elements), (iv) modulated elements (modulated sources of effort MSe and flow MSf, modulated transformer MTF, etc.) whose values depend on some other variables, (v) detectors (detector of effort De and detector of flow Df) which are sensors to measure some quantities of a system (Figure 3.4).

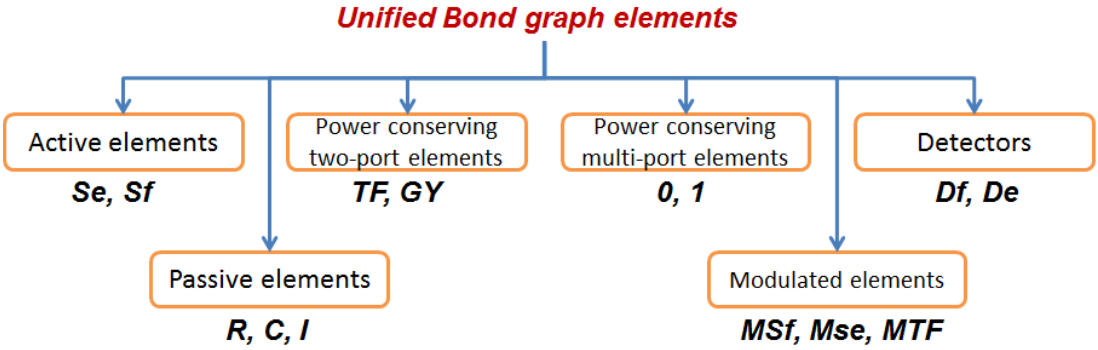


Figure 3.4: Bond graph elements.

For example, two physical systems are shown in Figure 3.5. Figure 3.5(a) represents the mechanical system with a mass m attached to a spring (spring stiffness K) and a dashpot (damping coefficient B); force $F(t)$ is applied on the mass which causes its motion (velocity $\dot{x}$). Figure 3.5(b) represents the electrical system with a current source i supplying current to a resistance R and a capacitance C in parallel; the value of i supplied by the current source depends on the value of $\dot{x}$ from the mechanical system.

The bond graph model of the combined system is given in Figure 3.5(c), where mass, spring, dashpot, input force, capacitance, and resistance are modeled using bond graph elements $I,\ C,\ R,\ Se,\ C,$ and R, respectively. Half-headed arrows represent the power exchange between various elements using power variable (e_i and $f_i : i \in \mathbb{N}^*$). For mechanical system, 1-junction represents common flow ($\dot{x}$) in the system which is measured by a detector element (detector of flow Df). For electrical system, 0-junction represents common effort (voltage in the system), and the input current is modeled using modulated source of flow MSf which

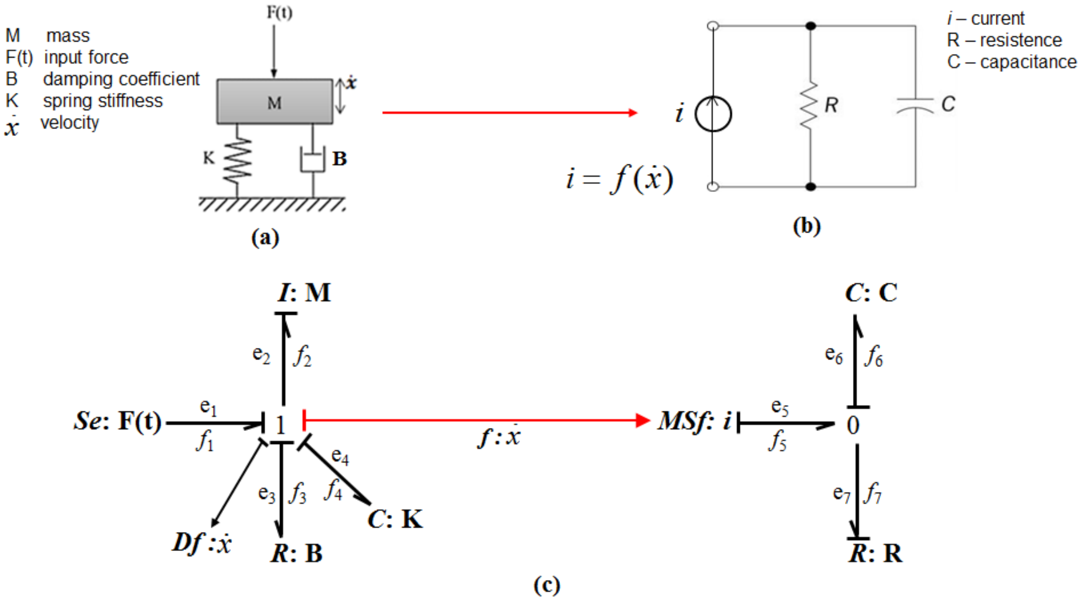


Figure 3.5: Two physical system exchanging information (a) mechanical system (b) electrical system (c) bond graph model of the combined system

depends on value of $\dot{x}$ from the mechanical system. This information exchange is modeled using information bond (full-headed arrow), which is a flow activated bond carrying flow information f.

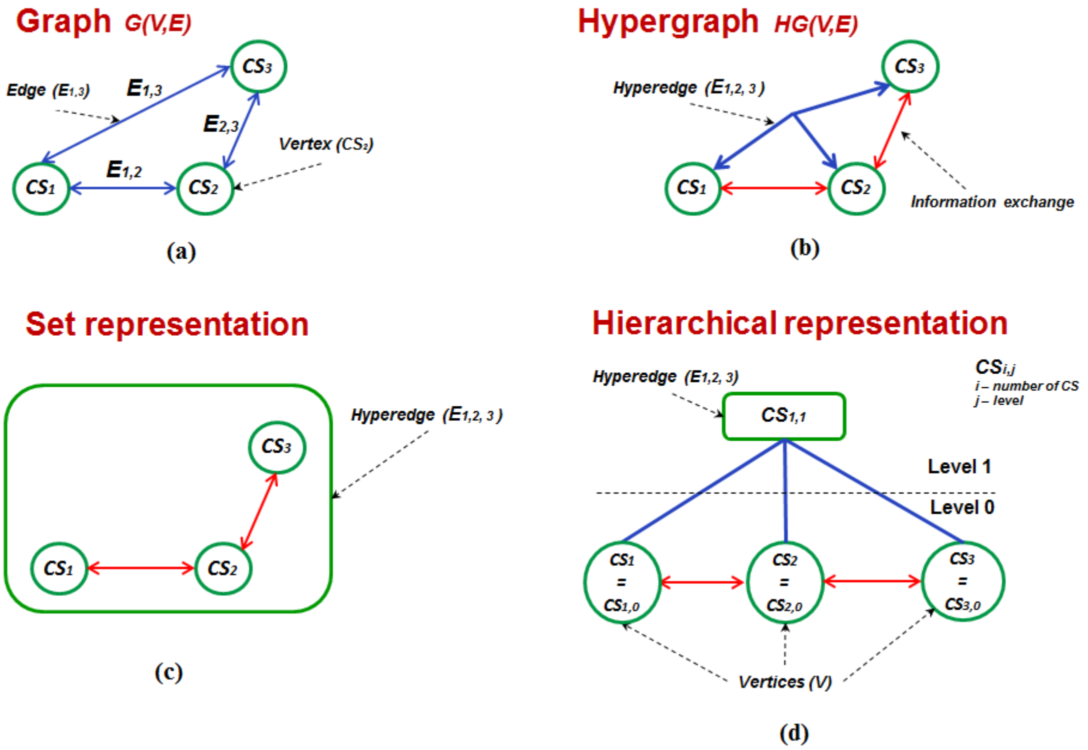
In this way, any physical system can be modeled using bond graph based on power exchange between its elements. Moreover, information exchange can be modeled using information bonds in bond graph. The dynamic equations of a system can be derived from its bond graph model using causal and structural properties. In addition, a bond graph model allows to perform structural analysis, and enables to deduce a variety of structural properties, such as: system controllability, observability, diagnosability, etc. Once it is performed, the designer receives a simple set of exploitable information that is obtained from the system structure.

More detail on the bond graph modeling approach is given in Appendix II.

3.3 Multilevel representation of a SoS

This section describes the multilevel representation of a SoS, and explains the organization of CSs in the SoS. The CSs can be organized in a SoS, while they respect the fundamental properties of the SoS.

For organizational modeling of a SoS, the graphical approaches are suitable due to its architectural and graphical vision for comprehension of the complex systems. The graph-based approaches are often applied for systems considered as independent entities. These approaches are able to model only binary relations, however, they do not support interconnections of different systems (Figure 3.6(a)).



(a) (b) (c) (d)

Figure 3.6: Graphical representation of CSs in a SoS (a) classical graph, (b) hypergraph, (c) set, and (d) hierarchical representations.

In Figure 3.6(a), three physical CSs (CS_1, CS_2, and CS_3) are shown as the vertices (V) of a classical graph $G(V, E)$ which are connected by edges (E). An edge can connect maximum two vertices, and fails to connect many vertices i.e., interconnections. Thus, it is a limitation of graph-based approach for modeling a SoS, because, a SoS has many interconnections among CSs.

Khalil et al. [2012] represented the interconnections of a SoS using a specific graphical formalism of the hypergraphs. A hypergraph has specific edges called hyperedges, and a hyperedge can have any number of vertices inside it (Figure 2.2 and Figure 3.6(b)).

In Figure 3.6(b), three physical CSs (CS_1, CS_2, and CS_3) are shown as the vertices (V) of a hypergraph $HG(V, E)$ which are connected by hyperedges (E). A hyperedge can connect any number of vertices, and it can be seen that three CSs are connected by a hyperedge $E_{1,2,3}$ while they can exchange information with each other. Figure 3.6(c) shows set representation of the organization of CSs where three physical CSs belong to the hyperedge $E_{1,2,3}$.

A SoS is a large-scale system which can be organized hierarchically in various abstraction levels as shown in Figure 3.6(d). Three physical CSs are represented by $CS_{1,0}$, $CS_{2,0}$, and $CS_{3,0}$ at the level-0, while their organization is represented by $CS_{1,1}$ at the level-1. Because, CSs at the higher levels (level$\neq$ 0) are just organizations of CSs at the lower levels, thus, $CS_{1,1}$ is the non-physical CS which represents the hyperedge $E_{1,2,3}$.

Now, we develop a generic representation of a SoS. Due to complexity of large-scale systems, it is suitable to represent them hierarchically. Large-scale systems can be organized in various levels of a SoS according to their complexity. Figure 3.7 shows a generic multilevel representation of a SoS. The generic representation of a SoS is given by z number of levels ($z = 0, 1, 2, 3...$). Each level of the SoS consists of component systems (CSs) which are organized in such a way that they can contribute to achieve the global mission of the SoS. Each CS in the SoS is associated with a particular mission, and these missions are achieved by the cooperation (organization and information exchange) among CSs at various levels of the SoS. Finally, their dynamic cooperation leads to achieve the global mission of the SoS.

Refer to Figure 3.7, any i^{th} CS at any j^{th} level of the SoS is denoted by $CS_{i,j}$, and the mission of $CS_{i,j}$ is denoted by $M_{i,j}$ ($i = 1, 2, 3...$; and $j = 0, 1, 2...$). All the CSs in the SoS can exchange information with each other using a communication channel in order to achieve their respective missions. At the lowest level-0,

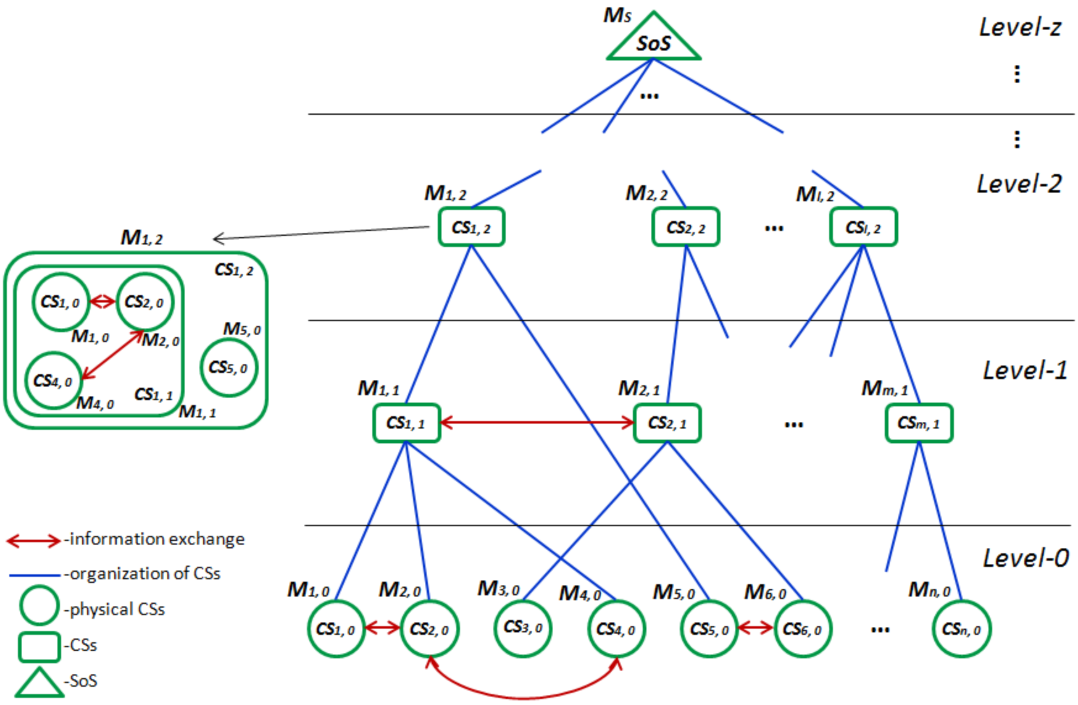


Figure 3.7: Generic multilevel representation of a SoS.

there are n numbers of CSs which are physical systems. The CSs at the level-0 can be defined as follows.

Definition 3.1: In a SoS, a CS at the level-0 $(CS_{i,j}, j = 0)$, is the independent physical system which cannot be divided further into other CSs. These CSs may be heterogeneous and multi-domain systems.

A CS other than the physical CSs is a set of CSs at the lower levels. These CSs at the higher levels can be defined as follows.

Definition 3.2: In a SoS, a CS at a level other than the level-0 $(CS_{i,j}, j \neq 0)$, is the independent non-physical system which is formed by the organization of some CSs at the levels lower than its own level.

All the CSs in a SoS are assigned with the specific missions. The mission of a CS can be defined as follows.

Definition 3.3: In a SoS, the mission of a CS is a set of objectives which are required to be achieved by the CS in order to fulfill the requirements of its normal functioning. However, the mission of a CS may keep on changing with time due to emergent behavior property of a SoS.

At the level-0, n physical CSs are assigned with the particular missions, for example mission $M_{n,0}$ is assigned to $CS_{n,0}$. The organizations of the physical CSs form m numbers of CSs at the level-1, which are dedicated to achieve some specific missions (for example mission $M_{m,1}$ for $CS_{m,1}$). Similarly, to achieve some specific missions at the level-2, l numbers of CSs are formed by the organizations of CSs at the lower levels. For example, to achieve the mission $M_{1,2}$, the CS $CS_{1,2}$ is formed whose composition is given as follows.

$$CS_{1,2} = \{CS_{1,1}, CS_{5,0}\}$$

$$CS_{1,1} = \{CS_{1,0}, CS_{2,0}, CS_{4,0}\}$$

In this way, it can be observed that the mission $M_{1,2}$ of $CS_{1,2}$ depends on the cooperation of $CS_{1,1}$ and $CS_{5,0}$. Moreover, it can be seen as the result of cooperation among the four physical CSs: $CS_{1,0}$, $CS_{2,0}$, $CS_{4,0}$, and $CS_{5,0}$. Finally, the SoS can be realized at the level z, and M_s is the global mission of the SoS. In this way, a SoS can be defined as follows.

Definition 3.4: A SoS at the highest level-z, is the integration of many CSs at the lower levels, cooperating with each other to achieve the global mission M_s of the SoS. The structure of a SoS changes with time due to its evolutionary development property.

Thus, a SoS can be described by the above definitions. In addition, there are some specific properties of a SoS which differentiate it from the traditional complex systems. Those properties are described in the following section.

3.4 Properties of a SoS from bond graph

Maier [1998] described the five properties to characterize a SoS as explained in the previous chapter. These properties are: operational independence of CSs, managerial independence of CSs, geographical dispersion of CSs, emergent behavior, and evolutionary and adaptive development. Here, we describe these properties based on the bond graph modeling approach. We use bond graph approach because the graphical representations described in the previous section don't include the dynamic models of physical CSs. The hyperedges of a hypergraph solved the problem of interconnection of CSs in a SoS, but there are following limitations of using hypergraph for modeling SoS:

- A hypergraph model of a SoS does not include the dynamic models of the physical CSs at the level-0.
- Absence of the theoretical methods to apply structural analysis on the hypergraph.

Thus, the bond graph approach is used for modeling of a SoS, which enables dynamic modeling of the physical CSs as described in the previous section. For modeling of the five properties of SoS, an example of three physical CSs is considered which are organized hierarchically (Figure 3.8).

In Figure 3.8(a), a hierarchical representation of a SoS is given which includes three physical CSs ($CS_{1,0}$, $CS_{2,0}$, and $CS_{3,0}$) at the level-0, and their organizational CS ($CS_{1,1}$) at the level-1. In Figure 3.8(b), set representation of the SoS is shown. Figure 3.8(c) shows the bond graph model of the SoS, where dynamic models of the physical CSs are given. It is assumed that the dynamics of $CS_{1,0}$ are composed of Se, I, MR, and C bond graph elements, whose values are Se_1, I_1, MR_1, and C_1, respectively. MR is a modulated resistance element because its value depends on external signal. Similarly, the dynamics of $CS_{2,0}$ and $CS_{3,0}$ are composed of some bond graph elements as shown in the figure. Information exchange among these CSs is modeled using information bonds (red arrows).

In a hierarchical representation of a SoS, CSs at the higher levels (level$\neq 0$) are the organizational CSs which are formed based on information from the CSs in its

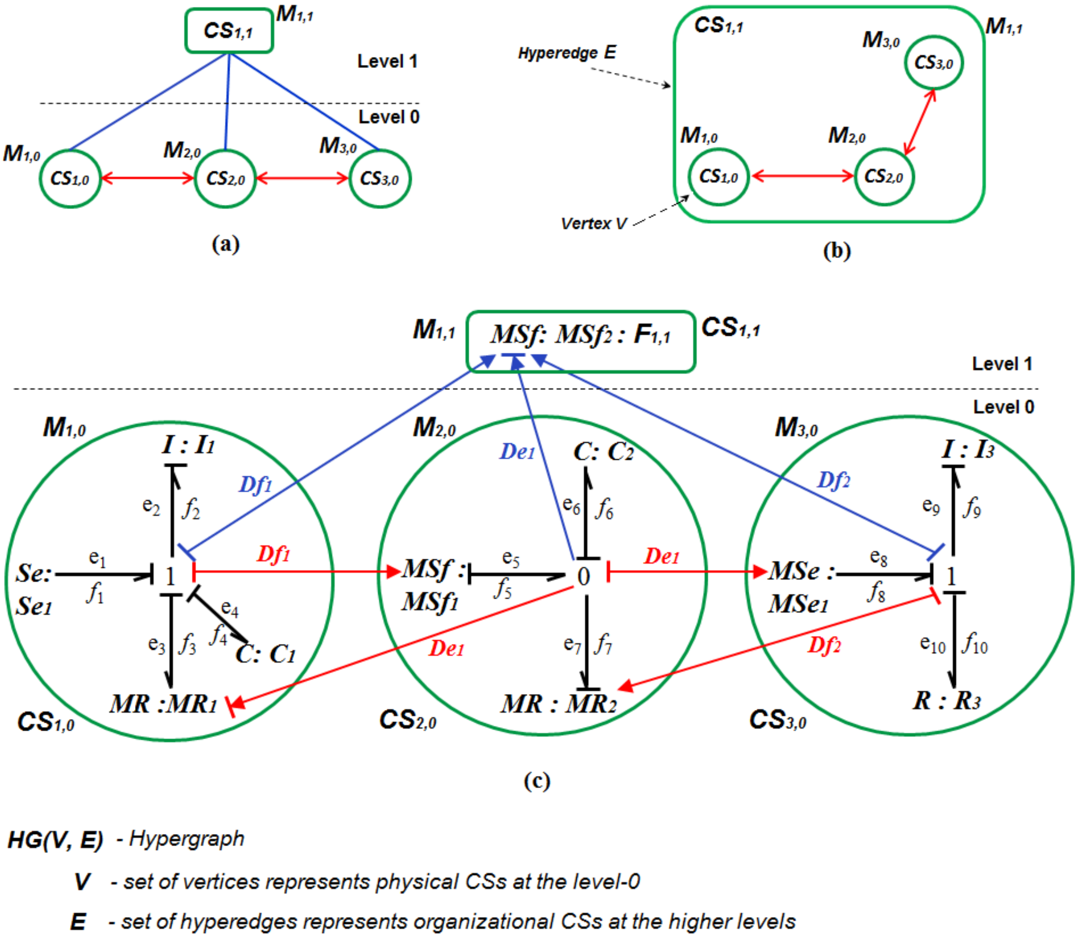


Figure 3.8: An example (a) hierarchical representation (b) set representation (c) bond graph model.

organization. We propose modeling of these organizational CSs using modulated sources (*MSf* and *MSe*) in bond graph. Refer to Figure 3.8(c), at the level-1, $CS_{1,1}$ is modeled using *MSf* which is formed based on information from three physical CSs ($CS_{1,0}$, $CS_{2,0}$, and $CS_{3,0}$) in its organization. This organization is modeled using information bonds (blue arrows).

Now, we can define CSs and their missions based on the bond graph modeling approach as follows.

Definition 3.5: In a SoS, a physical CS at the level-0 ($CS_{i,j}, j = 0$) is a set of bond graph elements which are involved in its dynamics.

Definition 3.6: In a SoS, the mission of a physical CS at the level-0 $(M_{i,j}, j = 0)$ is a set of bond graph power variables (e_i and $f_i : i \in \mathbb{N}^*$) which are involved in the dynamics of that CS.

For example in Figure 3.8(c), the component system $CS_{1,0}$ and its mission $M_{1,0}$ can be defined as follows.

$$CS_{1,0} = \{Se_1, I_1, C_1, R_1, Df_1\}$$

$$M_{1,0} = \{\{e_1, f_1\}, \{e_2, f_2\}, \{e_3, f_3\}, \{e_4, f_4\}\}$$

Where, Df_1 represents a sensor to measure the common flow f_i $(i = 1, 2, 3, 4)$ in the CS. In the same way, we can define CSs and missions at the higher levels.

Definition 3.7: In a SoS, a CS at a level other than the level-0 $(CS_{i,j}, j \neq 0)$ is a set of bond graph elements which are involved in its dynamics.

Definition 3.8: In a SoS, the mission of a CS at a level other than the level-0 $(M_{i,j}, j \neq 0)$ is a set of information variables received from the CSs in the organization of that CS.

For example in Figure 3.8(c), the component system $CS_{1,1}$ and its mission $M_{1,1}$ can be defined as follows.

$$CS_{1,1} = \{MSf_2\}$$

$$M_{1,1} = \{Df_1, De_1, Df_2\}$$

Where, Df_1, De_1, and Df_2 are sensor informations of the flow and effort received from three CSs in the organization of $CS_{1,1}$. We propose modeling of the higher level CSs using modulated sources *MSf* and *MSe*. These modulated sources are the functions of informations received from the CSs in the organization of the considered higher level CS. This function is denoted by $F_{i,j}$. For example in Figure 3.8(c), $CS_{1,1}$ is modeled by a modulated source of flow MSf_2 which can be defined as follows.

$$MSf_2 = F_{1,1}(Df_1, De_1, Df_2)$$

Refer to Figure 3.8, the physical CSs at the level-0 represent vertices (V) and the organizational CSs at the higher levels represent hyperedges (E) of a hypergraph $HG(V, E)$. Based on above definitions, we describe the fundamental properties of a SoS in the following subsections.

3.4.1 Operational independence of CSs

***Property 1.1*:** An organizational component system $CS_{i',j'\neq 0}$ in a SoS is operational independent if and only if:

$$CS_{i',j'} \in E = \{CS_{i,j}\}_{i\in\mathbb{N}^*, j\in\mathbb{N}^*}$$

***Property 1.2*:** A physical component system $CS_{i',j'=0}$ in a SoS is operational independent if and only if:

$$CS_{i',j'} \in V = \{CS_{i,j}\}_{i\in\mathbb{N}^*, j=0}$$

For example, in Figure 3.8; $CS_{1,1}$ is an organizational CS at the higher level. $CS_{1,1}$ belongs to a hyperedge which represents that it is operationally independent and can achieve its mission $M_{1,1}$ using its own resources. Furthermore, $CS_{1,0}$ is a physical CS at the level-0. $CS_{1,0}$ belongs to a vertex which represents that it is operationally independent and can achieve its mission $M_{1,0}$ using its own resources.

3.4.2 Managerial independence of CSs

***Property 2.1*:** Organizational component systems $CS_{i,j\neq 0}$ and $CS_{i',j'\neq 0}$ in a SoS are managerial independent if and only if:

$$\forall CS_{i,j}, CS_{i',j'} \in E : M_{i,j} \cap M_{i',j'} = \phi$$

***Property 2.2*:** Physical component systems $CS_{i,j=0}$ and $CS_{i',j'=0}$ in a SoS are managerial independent if and only if:

$$\forall CS_{i,j=0}, CS_{i',j'=0} \in V : M_{i,j} \cap M_{i',j'} = \phi$$

For example, in Figure 3.8; $CS_{1,1}$ is an organizational CS at the higher level. $CS_{1,1}$ has an independent mission $M_{1,1}$, and it can manage its mission independently. Furthermore, $CS_{1,0}$ and $CS_{2,0}$ are physical CSs at the level-0, and have their independent missions $M_{1,1}$ and $M_{1,2}$, respectively. $CS_{1,0}$ and $CS_{2,0}$ can manage their missions independent to each other.

3.4.3 Geographical dispersion of CSs

***Property 3.1*:** Organizational component systems $CS_{i,j\neq 0}$ and $CS_{i',j'\neq 0}$ in a SoS are dispersed geographically if and only if:

$$\forall CS_{i,j}, CS_{i',j'} \in E : CS_{i,j} \cap CS_{i',j'} = \{Df, De\}$$

***Property 3.2*:** Physical component systems $CS_{i,j=0}$ and $CS_{i',j'=0}$ in a SoS are dispersed geographically if and only if:

$$\forall CS_{i,j=0}, CS_{i',j'=0} \in V : CS_{i,j} \cap CS_{i',j'} = \{Df, De\}$$

For example, in Figure 3.8; $CS_{1,1}$ is an organizational CS at the higher level. $CS_{1,1}$ is not connected physically to any other CS, however, it can exchange information with other CSs. Furthermore, $CS_{1,0}$ and $CS_{2,0}$ are physical CSs at the level-0, and they are not connected physically but they exchange information (Df_1, De_1) between them. For geographically dispersed CSs, there should not be any exchange of mass or energy among them. Thus, $CS_{1,1}$, $CS_{1,0}$, and $CS_{2,0}$ are dispersed geographically.

3.4.4 Emergent behavior

***Property 4.1*:** Organizational component systems $CS_{i',j'\neq 0}$ in a SoS cooperate with each other to show emergent behavior if and only if:

$$\forall CS_{i',j'} \in E : \bigcup_{M_{i',j'}} \rightarrow M_{i,j}$$

***Property 4.2*:** Physical component systems $CS_{i',j'=0}$ in a SoS cooperate with each other to show emergent behavior if and only if:

$$\forall CS_{i',j'=0} \in V : \bigcup_{M_{i',j'=0}} \rightarrow M_{i,j\neq 0}$$

For example, in Figure 3.8; $CS_{1,1}$ is an organizational CS at the higher level. $CS_{1,1}$ can cooperate with other CSs to achieve the mission of a CS at the higher level than its own level. Furthermore, $CS_{1,0}$, $CS_{2,0}$, and $CS_{3,0}$ are physical CSs at the level-0, which cooperate with each other to achieve the mission $M_{1,1}$. The emergent behavior property explains that the global mission of a SoS cannot be achieved uniquely by any CS of the SoS. It can only be achieved by the cooperation of all the CSs in the considered SoS.

3.4.5 Evolutionary and adaptive development

***Property 5.1*:** An organizational component system $CS_{i,j\neq 0}$ in a SoS shows evolutionary and adaptive development if and only if:

$$\forall CS_{i,j} : (E = E \setminus \{CS_{i,j}\}) \vee (E = E \cup \{CS_{i,j}\})$$

***Property 5.2*:** A physical component systems $CS_{i,j=0}$ in a SoS shows evolutionary and adaptive development if and only if:

$$\forall CS_{i,j=0} : (V = V \setminus \{CS_{i,j=0}\}) \vee (V = V \cup \{CS_{i,j=0}\})$$

For example, in Figure 3.8; The higher level CSs (level≠0) belong to a set of hyperedges E, and the physical CSs (level=0) belong to a set of vertices V. These sets E and V may change due to evolutionary and adaptive development property of their organizational and physical CSs, respectively. For example, the structure of $CS_{1,1}$ may change due to removal of CSs from its organization, or due to addition of new CSs in its organization. Thus, $CS_{1,1}$, $CS_{1,0}$, $CS_{2,0}$, and $CS_{3,0}$ show evolutionary and adaptive development in the SoS. This property explains that a SoS is never fully formed or completed, and the structure of the SoS is keep on changing with time by addition or removal of CSs. Moreover, the global mission of the SoS may change, and accordingly CSs change their missions, which lead to change in their organizations to achieve the global mission.

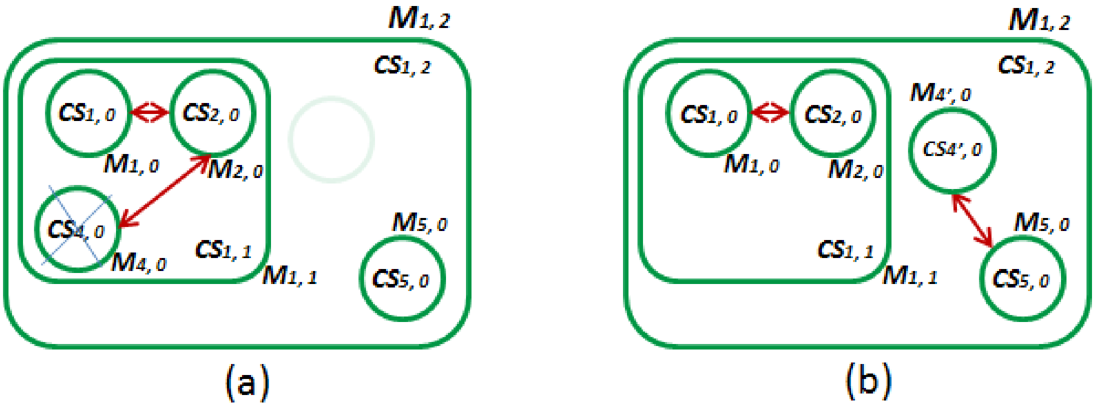


Figure 3.9: Evolutionary and adaptive development in a SoS: organization of $CS_{1,2}$ in (a) changes to (b)

Refer to Figure 3.9, the organization of $CS_{1,2}$ is considered in a SoS. It can be seen that the organization of $CS_{1,2}$ in Figure 3.9 (b) is different from its organization in Figure 3.9 (a). In Figure 3.9(b), one CS $CS_{4,0}$ is removed from the organization of $CS_{1,1}$, while a new CS $CS_{4',0}$ is added to the organization of $CS_{1,2}$. It represents the evolutionary and adaptive development property of a SoS

3.5 Methodology for multilevel modeling of a SoS

In this section, a methodology is described for multilevel modeling of a SoS based on the bond graph modeling approach. A generic multilevel representation of a SoS is already explained in the previous section (Figure 3.7). The first step in modeling is to represent a SoS according to the given generic multilevel representation (Figure 3.10). Then, the behavioral modeling of the physical CSs at the level-0, and the organizational modeling of the non-physical CSs at the higher level are performed. Finally, a unified multilevel bond graph model of a SoS is developed which combines the behavioral and organizational modeling approaches.

In the following subsections, the behavioral and the organizational modeling approaches are described based on bond graph.

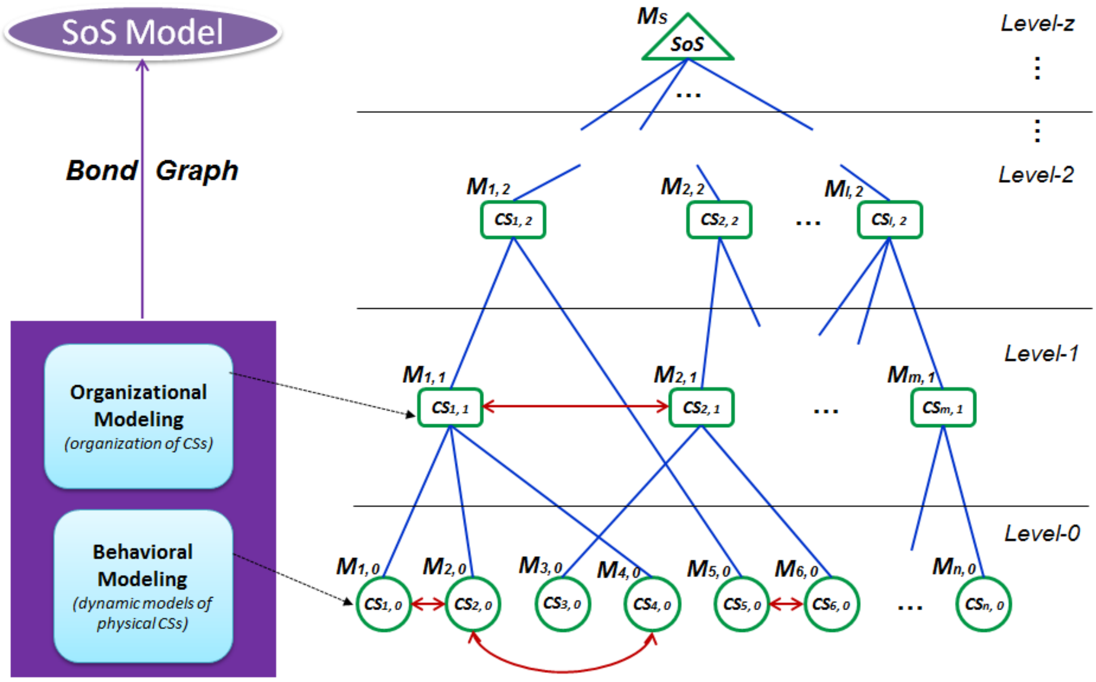


Figure 3.10: Methodology for multilevel modeling.

3.5.1 Behavioral modeling

This section highlights the need for behavioral modeling of the physical CSs in a SoS. Then, the behavioral modeling is explained using bond graph for an example of multi-robot SoS.

A. Problem statements

Most of the existing SoS models (like agent-based, hypergraph, set theory, and game theory modeling approaches) are based on the organizational modeling approach, which do not include the dynamic behavioral models of the physical CSs, which can result in the following problems.

- If the behavioral models of the physical CSs are not included, then it is difficult to describe the behavior of a SoS in case of presence of behavioral perturbations. For example, if status of a physical CS $(CS_{i,j}, j = 0)$ is faulty, then, this fault can propagate to the higher level CSs $(CS_{i,j}, j \neq 0)$, and finally can lead to failure of the global mission (M_s) of a SoS. In this case, it is important to know the origin of fault at the level-0 in order to anticipate on the evolution of the whole SoS.

- Moreover, it is difficult to apply control and supervision strategies to recover a SoS from the faulty situations occurred in the physical CSs.

On contrary, if the behavioral models of the physical CSs are included, then, it is easier to identify the perturbations, and to describe the behavior of a SoS, accordingly. For example, if status of a physical CS is faulty, then, based on its behavioral model we can identify the fault, and can apply some reconfiguration strategies to recover the SoS from faulty to normal situation.

Thus, for the whole supervision of a SoS, it is required to include the behavioral models of the physical CSs in the organizational model of the SoS.

The contribution here is to use a unified bond graph model-based approach for modeling the dynamic behavior of the physical CSs ($CS_{i,j}, j = 0$), and to extend this approach for modeling the organization of the higher level CSs ($CS_{i,j}, j \neq 0$) and their information exchange.

Knowing that in the bond graph modeling approach, the theory of structural analysis is well developed, thus, in case of bond graph model of a SoS, the structural properties can be derived for control and supervision interests.

B. Bond graph based behavioral modeling of the physical CS

Here, we consider an example of multi-robot system to explain bond graph based behavioral modeling of the physical CSs at the level-0. Let us consider a group of mobile robots working collectively to achieve a common mission (Figure 3.11). This multi-robot system can be considered as a SoS, because each mobile robot in the SoS is operationally and managerially independent, and can complete its mission using its own resources. Furthermore, they are dispersed geographically with a continuous exchange of information among them; finally, they exhibit emergent behavior and evolutionary development in the SoS.

Refer to Figure 3.11, a multi-robot SoS is shown, in which, three mobile robots named ‘Robotino’, are working collectively for a common mission. Robotino is a

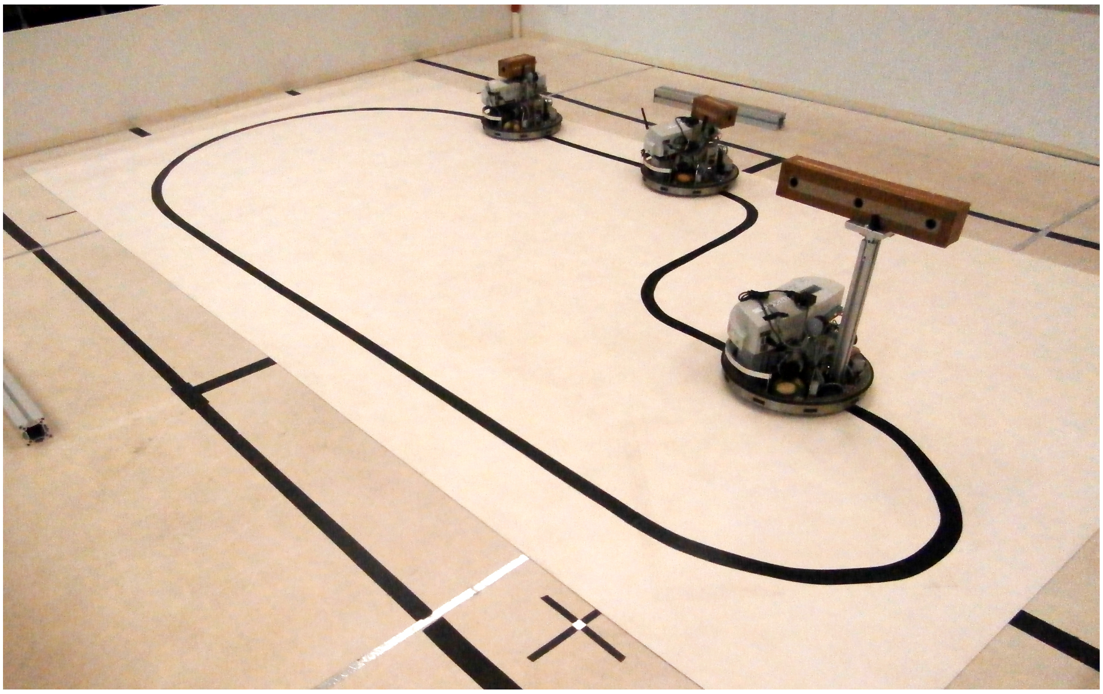


Figure 3.11: A multi-robot SoS.

mobile robot with three omnidirectional drive units, it is developed by the Festo company. Robotino uses its frontal infrared distance sensor to determine the interdistance with other Robotino (Figure 3.12).

Robotino is a physical CS of the considered multi-robot SoS. It is required to develop the dynamic model of Robotino in order to analyze its behavior in the SoS. The dynamic model of Robotino is developed based on the bond graph modeling approach. The structural analysis of the bond graph model enables the whole supervision of the SoS. The top view of Robotino, and its drive unit are shown in Figure 3.13 and 3.14, respectively.

The dynamic model of Robotino is developed considering the following dynamics: 1) longitudinal, lateral, and yaw dynamics of the centre of mass, and 2) the drive unit (motor-wheel systems) dynamics. The following modeling assumptions are made: 1) Robotino moves in a plane surface, 2) the road is uniform and the suspension, roll, and pitch dynamics are not considered, and 3) each wheel is independently driven by the dc motor.

Figure 3.12: Festo's Robotino.

The word bond graph of Robotino is shown in Figure 3.15, which gives block representation of the different considered dynamics of the system. Three motor-wheel systems provides traction to the body of Robotino, for which longitudinal, lateral, and yaw dynamics are considered.

The voltage source provides input U_{0j} (j is wheel number, j=1, 2, and 3) to the electrical part of the motor and current i_j is generated. After some losses in electrical part, remaining voltage U_j is used to generate angular velocity $\dot{\theta}_{ej}$ on the motor axle i.e., mechanical part. The mechanical part generates torque $k_{ej}.i_j$ (k_{ej} is torque constant of the motor). In the transmission part, gears are used to generate output angular velocity $\dot{\theta}_{sj}$ and torque $N_j.k_{ej}.i_j$ (N_j is gear ratio) of the wheel axle. Finally, contact force F_{xj} and linear velocity $r_j.\dot{\theta}_{sj}$ (r_j is the radius of wheel) are transferred to the body of Robotino, where longitudinal, lateral, and yaw dynamics are generated.

Let us consider the dynamics of j^{th} motor-wheel system (j=1, 2, and 3), this system consists of the following parts: electrical and mechanical parts of the motor, transmission, and wheel part. The bond graph model of the system is

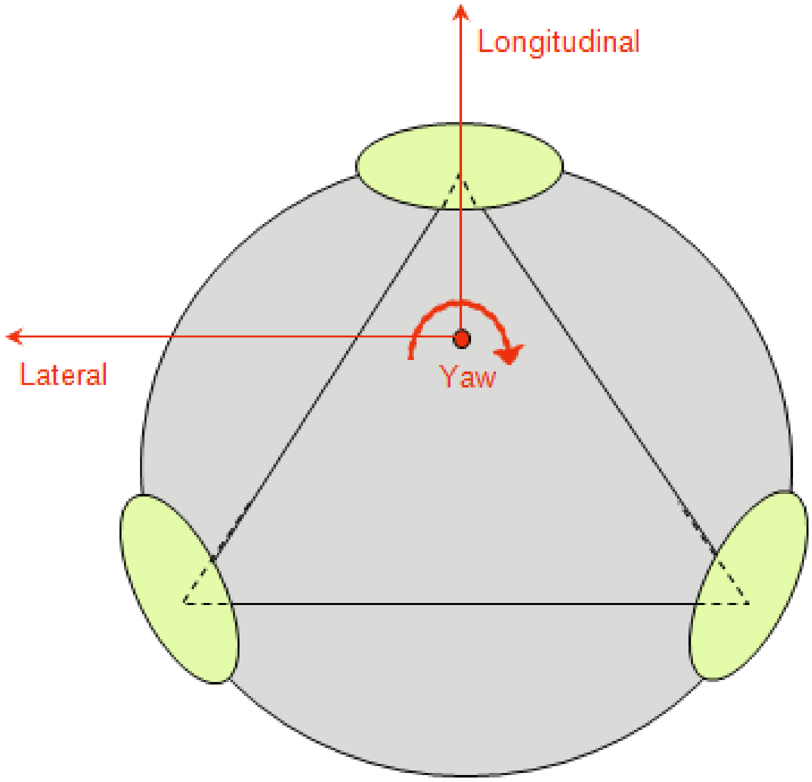


Figure 3.13: Schematic of Robotino.

given in Figure 3.16.

Refer to Figure 3.16, in the electrical part of the motor U_{0j}, i_j, L_j, R_j , and k_{ej} are input voltage, current, inductance, resistance, and torque constant of the motor, respectively. In the mechanical part of the motor J_{ej}, f_{ej}, $\dot{\theta}_{ej}$, w_j, and K_j are axle inertia, viscous friction, angular velocity, backlash torque, and axle rigidity of the motor, respectively. In the wheel part, N_j, J_{sj}, f_{sj}, $\dot{\theta}_{sj}$, r_j, and F_{xj} are gear ratio, inertia, viscous friction, angular velocity, radius, and longitudinal contact force of the wheel, respectively.

The full-headed arrows corresponding to current i_j in the motor, angular velocity $\dot{\theta}_{ej}$ of the motor axle, and angular velocity of the wheel $\dot{\theta}_{sj}$ represent the sensors Df to measure the value of the corresponding parameter. The bond graph elements *Se, MSe, I, R, C, TF, GY,* 0-junction, and 1-junctions are used to model the system, the gyrator element *GY* models the domain change from electrical to mechanical.

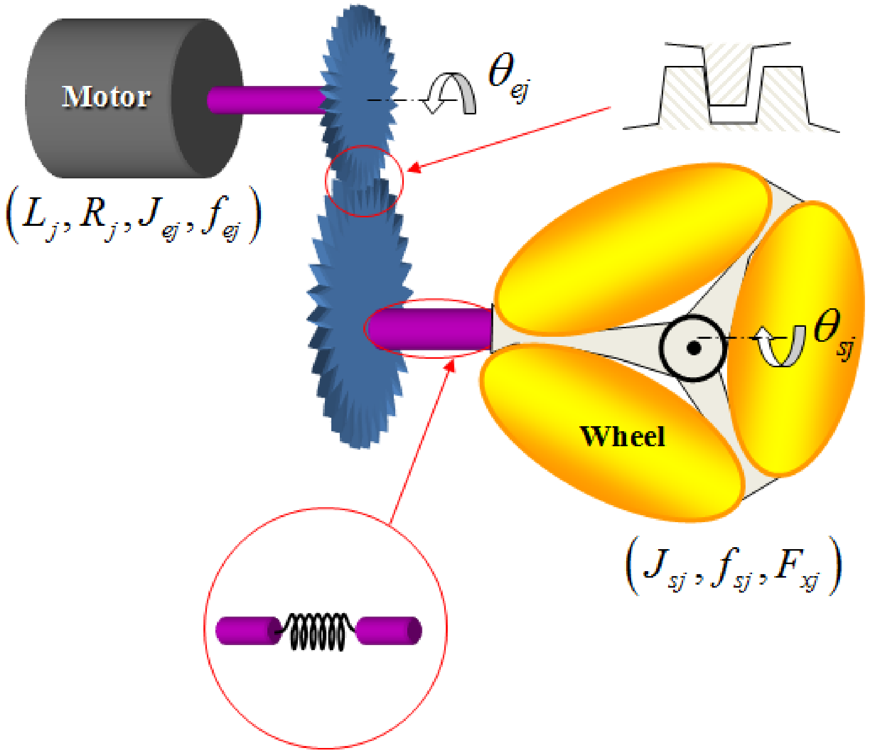


Figure 3.14: Schematic of the motor-wheel system of Robotino.

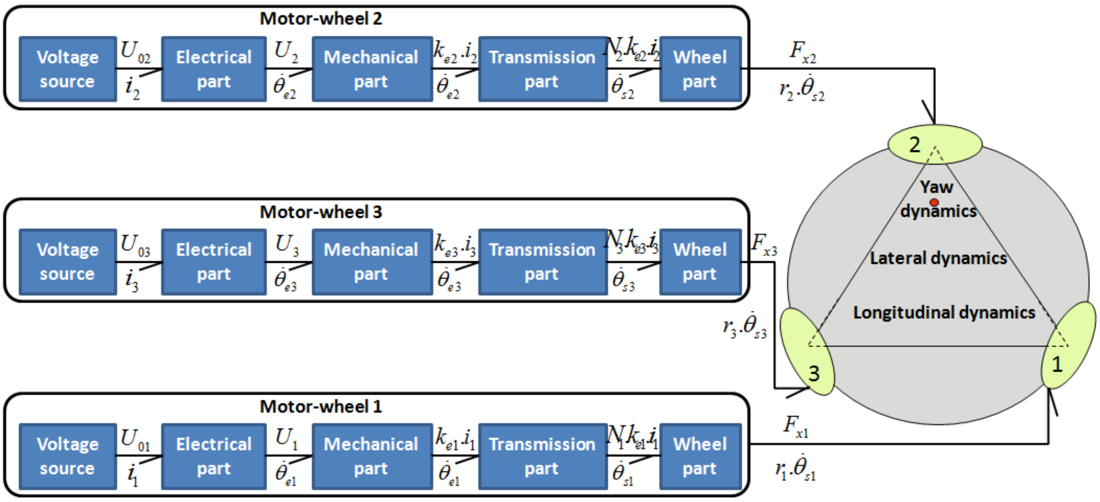


Figure 3.15: Word bond graph model of Robotino.

The dynamic behavioral model of the system can be derived from the bond graph model based on its causal and structural properties. The power variables

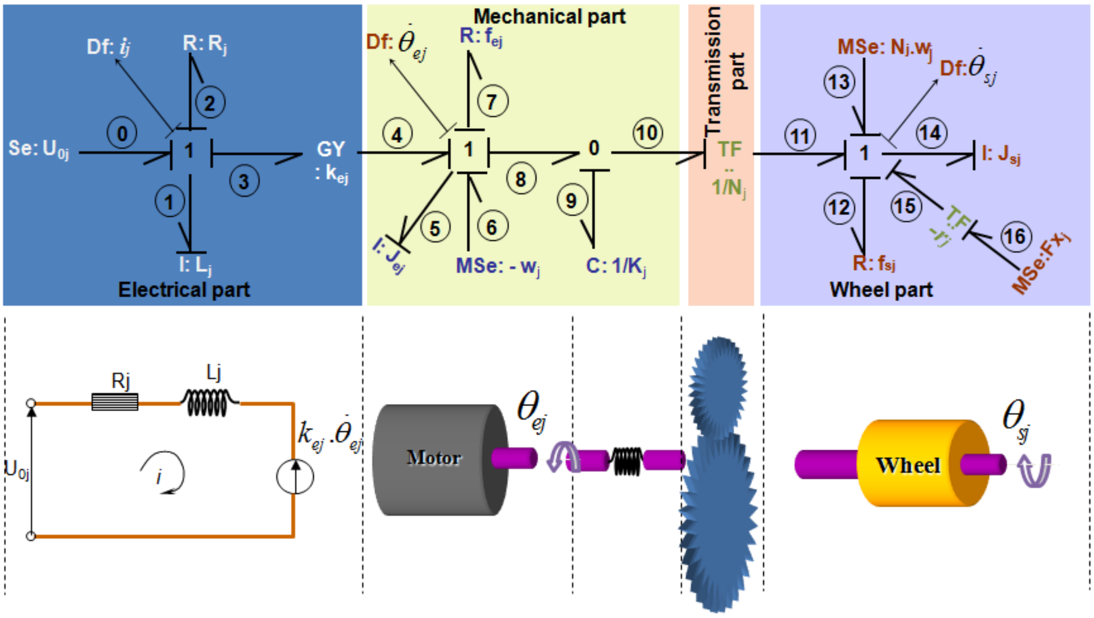


Figure 3.16: Bond graph model of the motor-wheel system of Robotino.

(effort e_n and flow f_n) of the bond graph model are associated with each power bond, where n (n=1, 2, 3,...) is the bond number. The system equations can be derived as follows:

(a) System states:

$$p_j = \int e_1; \qquad p_{ej} = \int e_5; \qquad Q_j = \int f_9; \qquad p_{sj} = \int e_{14}$$

(b) Junction structural equations:

$$1 - junction \begin{cases} f_0 = f_1 = f_2 = f_3 = i_j = \frac{p_j}{L_j} \\ e_0 - e_1 - e_2 - e_3 = 0 \end{cases}$$
$$1 - junction \begin{cases} f_4 = f_5 = f_6 = f_7 = f_8 = \dot{\theta}_{ej} = \frac{p_{ej}}{J_{ej}} \\ e_4 - e_5 + e_6 - e_7 - e_8 = 0 \end{cases}$$
$$0 - junction \begin{cases} f_8 - f_9 - f_{10} = 0 \\ e_8 = e_9 = e_{10} = k_j Q_j \end{cases}$$
$$1 - junction \begin{cases} f_{11} = f_{12} = f_{13} = f_{14} = f_{15} = \dot{\theta}_{sj} = \frac{p_{sj}}{J_{sj}} \\ e_{11} - e_{12} + e_{13} - e_{14} + e_{15} = 0 \end{cases}$$

(c) Behavioral equations:

$$\begin{array}{llll}
e_0 = U_{0j}; & f_1 = \frac{1}{L_j}\int e_1; & e_2 = R_j f_2 & \\
e_3 = k_{ej} f_4; & e_4 = k_{ej} f_3; & f_5 = \frac{1}{J_{ej}}\int e_5 & \\
e_6 = -w_j; & e_7 = f_{ej}\dot{\theta}_{ej}; & f_8 = \dot{\theta}_{ej} & \\
e_9 = K_j \int f_9; & f_{10} = N_j \dot{\theta}_{sj}; & e_{11} = N_j K_j \int f_9 & \\
e_{12} = f_{sj} f_{12}; & e_{13} = N_j w_j; & f_{14} = \frac{1}{J_{sj}}\int e_{14}; & e_{15} = r_j F_{xj}
\end{array}$$

Based on the above equations; (a) system states, (b) junction structural equations, and (c) behavioral equations, we can derive the (d) dynamic equations of the system from the junction law corresponding to bonds 0, 1, 2, 3; bonds 4, 5, 6, 7, 8; and bonds 11, 12, 13, 14, 15.

(d) Dynamic equations:

$$L_j \frac{di_j}{dt} = U_{0j} - R_j i_j - k_{ej}\dot{\theta}_{ej} (\text{electrical} \quad \text{part})$$

$$J_{ej} \frac{d\dot{\theta}_{ej}}{dt} = -f_{ej}\dot{\theta}_{ej} + k_{ej} i_j - w_j - K_j(\theta_{ej} - N_j \theta_{sj}) (\text{mechanical} \quad \text{part})$$

$$\dot{\theta}_{ej} = N_j \dot{\theta}_{sj} (\text{transmission} \quad \text{part})$$

$$J_{sj} \frac{d\dot{\theta}_{sj}}{dt} = -f_{sj}\dot{\theta}_{sj} + N_j w_j + N_j K_j(\theta_{ej} - N_j \theta_{sj}) - r_j F_{xj} (\text{wheel} \quad \text{part})$$

Refer to Figure 3.17, V_x, V_y, and $\dot{\gamma}$ denote longitudinal, lateral, and yaw velocities, respectively. F_{x1}, and F_{x3} are longitudinal contact forces; and F_{y1}, F_{y2}, and F_{y3} are lateral contact forces. The dimensions of Robotino are denoted by Z, N, and L.

The bond graph models for longitudinal, lateral, and yaw dynamics of Robotino are given in Figure 3.18, 3.19, and 3.20, respectively.

Where, M and I_z denote mass and inertia of Robotino, respectively. From the bond graph models given in Figure 3.18, 3.19, and 3.20, the dynamic equations can be derived in the same way as described before for the motor-wheel system. The equations for longitudinal, lateral, and yaw dynamics are given in (3.1)-(3.3).

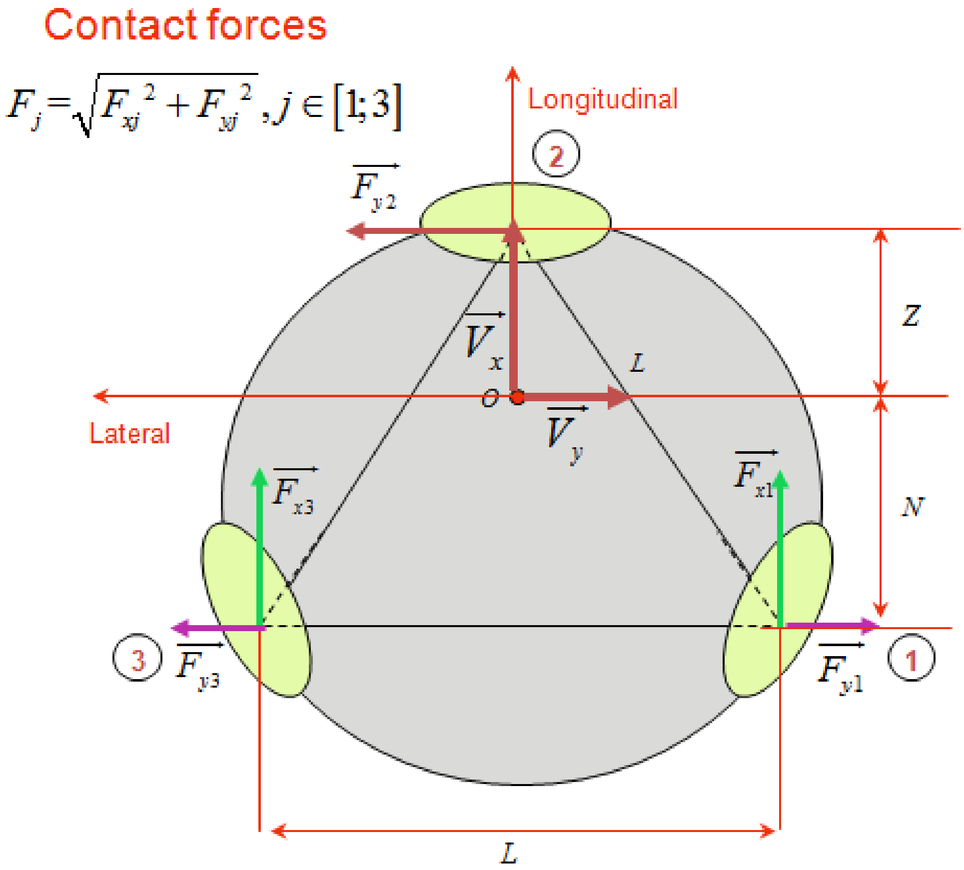


Figure 3.17: Representaion of the contact forces on Robotino.

$$M.\dot{V}_x = F_{x1} + F_{x3} - f_m.V_y = (F_1 + F_3)\,.\cos\left(\frac{\pi}{6}\right) - f_m.V_y \tag{3.1}$$

$$M.\dot{V}_y = F_{y1} - F_{y3} - F_{y2} - f_n.V_y = (F_1 - F_3)\,.\sin\left(\frac{\pi}{6}\right) - F_2 - f_n.V_y \tag{3.2}$$

$$\begin{aligned} I_Z.\ddot{\gamma} &= (F_{x1} - F_{x3})\,.\frac{L}{2} + F_{y2}.Z + (F_{y1} - F_{y3})\,.N \\ &= (F_1 - F_3)\,.\frac{L}{2}.\cos\left(\frac{\pi}{6}\right) + F_2.Z + (F_1 - F_3)\,.N.\sin\left(\frac{\pi}{6}\right) \end{aligned} \tag{3.3}$$

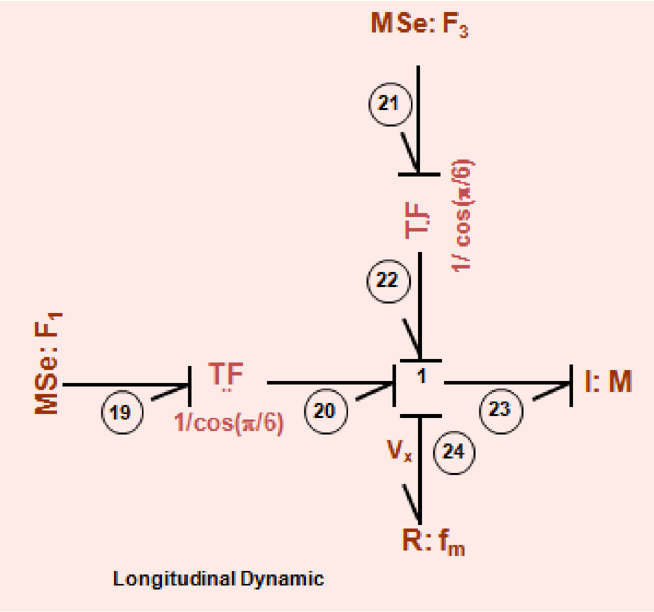


Figure 3.18: Bond graph model of longitudinal dynamics.

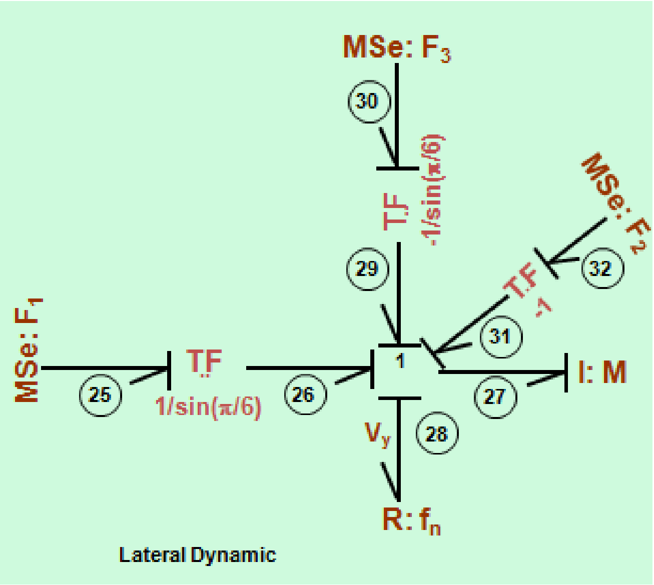


Figure 3.19: Bond graph model of lateral dynamics.

Finally, the complete bond graph model is presented in Figure 3.21, three electromechanical systems represent the models of the motor-wheel systems. The bond graph models of longitudinal, lateral, and yaw dynamics are combined with motor-wheel systems to develop the complete model of Robotino.

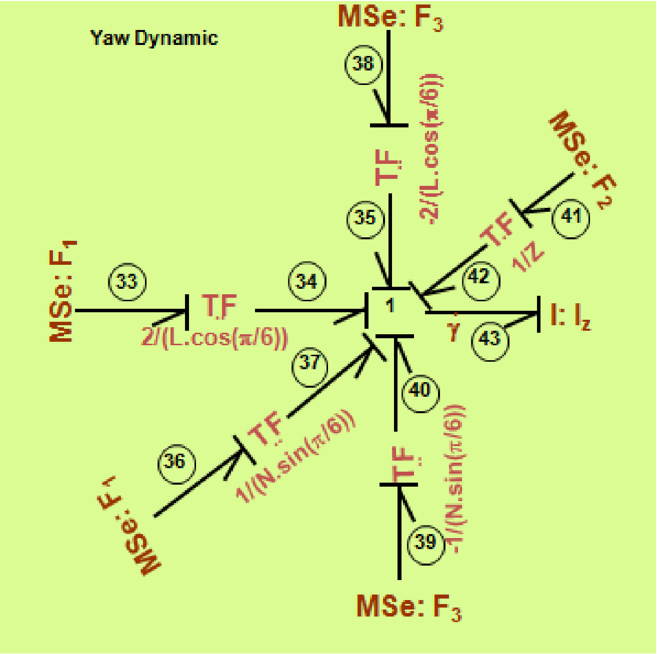


Figure 3.20: Bond graph model of yaw dynamics.

C. Bond graph based FDI

The developed model of Robotino can be used for model-based Fault Detection and Isolation (FDI). Once the FDI analysis is performed on the model, it is possible to detect and isolate the faults online, and subsequently, to analyze the effect of a faulty physical CS on the whole SoS. Finally, a model-based reconfiguration strategy can be developed to recover the SoS from faulty to normal situation.

By making use of the bond graph approach, the obtained model of a system contains several attractive properties such as: behavioral, structural, and causal that can be exploited not only for modeling, but also for analysis and synthesis. Hence, this representation enables conclusions to be made about the system from a structural point of view, i.e., without knowing their numerical values. Its causal structure was initially exploited to determine structural conditions of controllability and observability (Sueur and Dauphin-Tanguy [1991]), and diagnosability (Ould-Bouamama et al. [2003]).

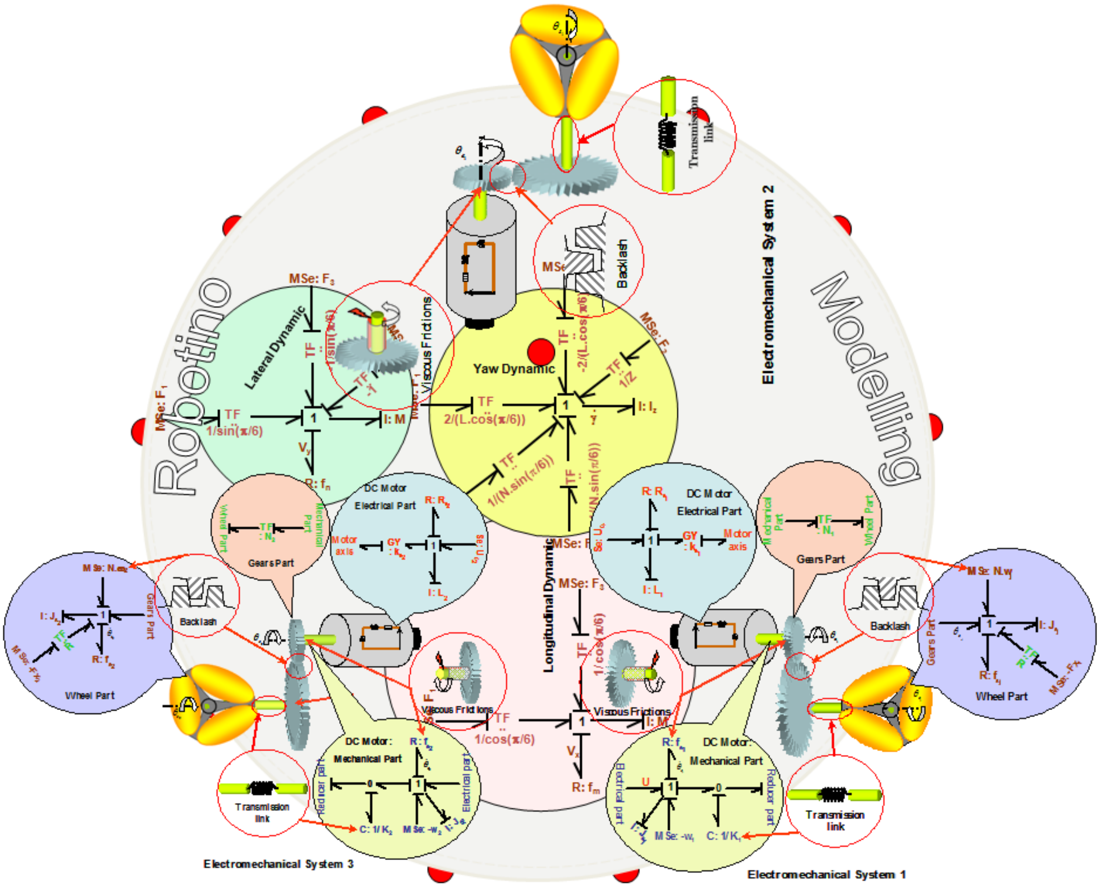


Figure 3.21: Complete behavioral model of Robotino.

The bond graph based FDI is well established in literature (Samantaray and Bouamama [2008]). In this method, the bond graph model is manipulated to obtain a FDI model by following procedure: 1) all the sensors are dualized into signal source of effort or flow (SSe or SSf) and, 2) the considered bond graph model is assigned a preferred derivative causality. Then, this model is used to generate Analytical Redundancy Relations (ARRs), which are obtained by following the causal path from the known to unknown variables. The evaluation of these ARRs is performed using sensor' data, which defines the difference between the expected and observed values of parameters, this difference is called residual. Based on ARRs evaluation, a Fault Signature Matrix (FSM) is developed which enables to detect and isolate faults at any point of time.

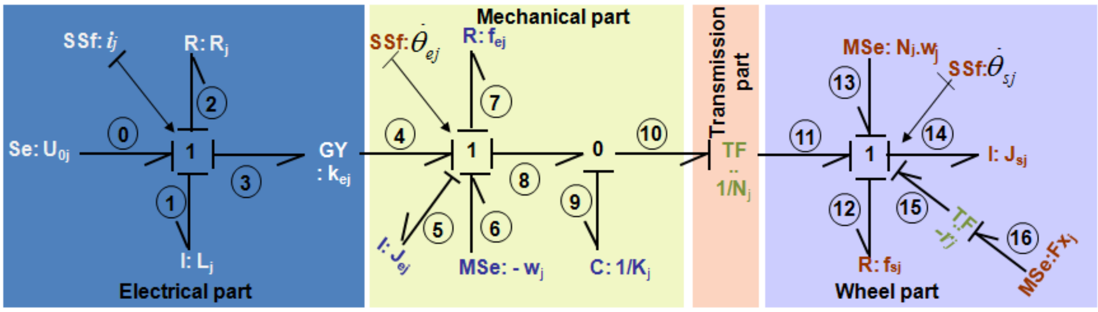


Figure 3.22: Bond graph model of the motor-wheel system in preferred derivative causality.

Here, we consider faults on the motor-wheel systems of Robotino. The bond graph model of the motor-wheel systems for FDI is given in Figure 3.22.

In Figure 3.22, three detectors to measure i_j, $\dot{\theta}_{ej}$, and $\dot{\theta}_{sj}$ are replaced by the signal sources of flow (SSf). These SSf act like input flow sources based on the data received from sensors. Then, the bond graph model is assigned a preferred derivative causality. Finally, three ARRs can be obtained corresponding to three 1-junctions where SSf are connected.

$$ARR_{1j} : U_{0j} - R_j i_j - L_j \frac{di_j}{dt} - k_{ej}\dot{\theta}_{ej} = 0 \tag{3.4}$$

$$ARR_{2j} : k_{ej} i_j - J_{ej}\frac{d\dot{\theta}_{ej}}{dt} - f_{ej}\dot{\theta}_{ej} - w_j - K_j(\theta_{ej} - N_j\theta_{sj}) = 0 \tag{3.5}$$

$$ARR_{3j} : N_j w_j + N_j K_j(\theta_{ej} - N_j\theta_{sj}) - J_{sj}\frac{d\dot{\theta}_{sj}}{dt} - f_{sj}\dot{\theta}_{sj} - r_j F_{xj} = 0 \tag{3.6}$$

The evaluation of ARRs gives residuals which allow to obtain FSM. Three residuals (r_{1j}, r_{2j}, and r_{3j}) can be written corresponding to three ARRs as follows:

$$r_{1j} = U_{0j} - R_j i_j - L_j \frac{di_j}{dt} - k_{ej}\dot{\theta}_{ej} \tag{3.7}$$

$$r_{2j} = k_{ej} i_j - J_{ej}\frac{d\dot{\theta}_{ej}}{dt} - f_{ej}\dot{\theta}_{ej} - w_j - K_j(\theta_{ej} - N_j\theta_{sj}) \tag{3.8}$$

$$r_{3j} = N_j w_j + N_j K_j(\theta_{ej} - N_j \theta_{sj}) - J_{sj}\frac{d\dot{\theta}_{sj}}{dt} - f_{sj}\dot{\theta}_{sj} - r_j F_{xj} \tag{3.9}$$

Here, it is assumed that the sensors are ideal. FSM for j^{th} motor-wheel system of Robotino is given in Table 3.1.

Table 3.1: FSM for j^{th} motor-wheel system of Robotino

Components	r_{1j}	r_{2j}	r_{3j}	M_b	I_b
J_{ej}	0	1	0	1	0
f_{ej}	0	1	0	1	0
J_{sj}	0	0	1	1	0
f_{sj}	0	0	1	1	0
R_j	1	0	0	1	0
L_j	1	0	0	1	0
w_j	0	1	1	1	1
U_{0j}	1	0	0	1	0
F_{xj}	0	0	1	1	0

In Table 3.1, the rows represent the component's signatures, and the columns represent: components of the system, three residuals, fault monitorability (M_b), and fault isolablility (I_b), respectively. If a component is presented in an ARR then '1' is assigned in the corresponding entry of FSM (means that the residual is sensitive to a fault in this component), otherwise '0' is assigned. It can be noticed from Table 3.1 that w_j has unique fault signature, thus, this fault can be isolated; and all the faults are monitorable because each fault is sensitive to at least one residual.

In the same way, bond graph models can be obtained for all the mobile robots (Robotino) in the multi-robot SoS. Futhermore, FDI can be applied on bond graph models, which enables to analyze the effect of a faulty physical CS (Robotino) on the whole SoS. Finally, a model-based reconfiguration strategy can be developed to deal with faulty situations in the SoS.

In this way, the behavioral model of a physical CS can be obtained using bond graph modeling approach. In addition, the causal and structural analysis of a bond graph model enables to apply control and supervision strategies.

3.5.2 Organizational modeling

In the previous section, the behavioral modeling of the physical CSs ($CS_{i,j=0}$) is explained based on bond graph. In this section, we extend bond graph model to the organizational modeling of the higher level CSs ($CS_{i,j\neq0}$), in order to realize the complete model of a SoS using single modeling technique i.e., bond graph.

In a bond graph model, many bond graph elements are controlled by a signal. These elements are called 'modulated elements' and are highlighted by a letter 'M' preceding the element symbol, for example, modulated source of effort MSe, modulated source of flow MSf, modulated transformer MTF, modulated resistance MR, etc.

We propose modeling of the higher level CSs ($CS_{i,j\neq0}$) using MSf and MSe. In addition, information exchanges (signals) in a SoS are modeled using 'information bonds'. Contrary to power bonds in bond graph, information bonds are used only for detection (detector of effort De and detector of flow Df), and do not contribute to any power flow. These information bonds are represented by the full-headed arrows in a bond graph model.

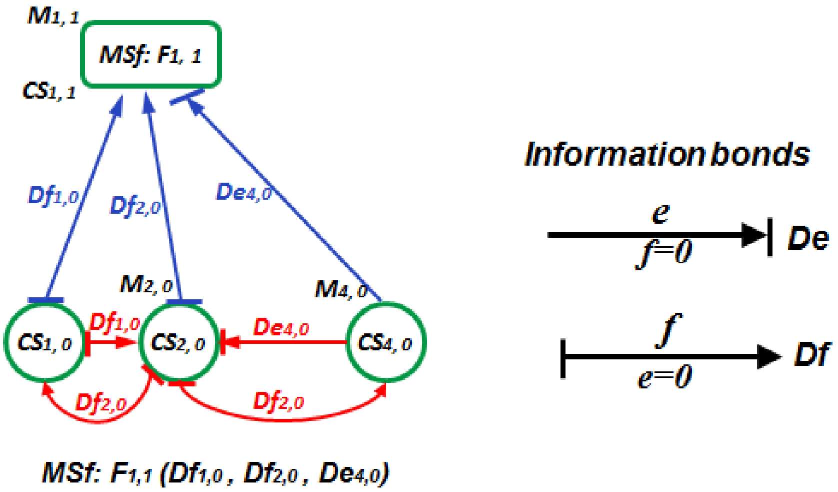


Figure 3.23: Organizational modeling.

In Figure 3.23, the organization of $CS_{1,1}$ is considered from the generic SoS representaion in Figure 3.10. $CS_{1,1}$ is modeled with MSf, which is an organization of $CS_{1,0}$, $CS_{2,0}$, and $CS_{4,0}$. This MSf is a function of information of flow from $CS_{1,0}$ and $CS_{2,0}$, and effort from $CS_{4,0}$. This function is denoted by $F_{1,1}$. The organizational bonds are denoted by blue arrows, while information exchanges among $CS_{1,0}$, $CS_{2,0}$, and $CS_{4,0}$ are denoted by red arrows (both blue and red arrows represent information bonds in bond graph).

3.5.3 Multilevel bond graph model of a SoS

In this section, a multilevel bond graph model of a SoS is developed which combines the behavioral and organizational modeling approaches. The generic multilevel bond graph model of a SoS is shown in Figure 3.24. This model is developed in the same way as given in Figure 3.10 with z number of levels. The model combines the organizational and behavioral modeling approaches.

Refer to Figure 3.24, the cooperation (organization and information exchange) among CSs at various levels is modeled using modulated elements MSf and MSe, and information bonds. At the level-0, the physical CSs ($CS_{i,j}, i \in \mathbb{N}^*, j = 0$) include the bond graph models, which are represented by $BG_{i,0}$. $BG_{i,0}$ are the bond graph models of complex mechatronic systems, which may be heterogeneous and multi-domain physical systems. These systems must respect the properties of a SoS. For example, the bond graph model of Robotino is shown inside $BG_{1,0}$ in Figure 3.24, which is described as the physical CS in previous section.

In Figure 3.24, there are n number of physical CSs at the level-0. These $CS_{i,0}$ are operationally and managerially independent systems, with continuous exchange of information among them. For example, $CS_{1,0}$ includes the bond graph model of Robotino, and it can operate independently to achieve its own mission $M_{1,0}$. $CS_{1,0}$ exchanges information with $CS_{2,0}$ which is represented by the flow activated bonds $Df_{1,0}$ and $Df_{2,0}$. In the same way, modeling of the other physical CSs can be described which include bond graph models $BG_{i,0}$ of their dynamic behavior.

The higher level CSs (level$\neq$0) are non-physical systems, which are modeled with MSf and MSe. Each MSf/MSe is defined by a function $F_{i,j}$ (j$\neq$0). This function depends on information (effort e_i and flow f_i) from CSs included in the organization of the considered CS. For example, at the level-2, $CS_{1,2}$ is modeled with MSf, which is an organization of $CS_{1,1}$ and $CS_{5,0}$. This MSf is defined by a function $F_{1,2}$ which depends on information of flow variables from $CS_{1,1}$ and

$CS_{5,0}$. Thus, this MSf can be given by $MSf = F_{1,2}(Df_{1,1}, Df_{5,0})$. Similarly, modeling of the other organizational CSs can be described in the SoS.

In this way, all the CSs in a SoS can be described, and finally, the SoS can be realized at the highest level (level-z) with its global mission M_s.

3.6 Summary of the chapter

A SoS can be organized into various levels based on its complexity. In a SoS, CSs at the lowest level (level-0) represent the physical CS, while CSs at the higher levels (level≠0) are the non-physical CSs, which are formed by the organizations of CSs at the levels lower than their own levels. The fundamental properties of a SoS include: operational independence, managerial independence, geographical dispersion, emergent behavior, and evolutionary development. These properties are mathematically described based on the graphical approach.

In this chapter, a method for the organizational and behavioral modeling of a class of SoS (engineering mechatronic systems) is proposed based on the bond graph modeling approach. This is achieved by the dynamic modeling (behavioral modeling) of the physical CSs; and then extending this behavioral modeling to the organizational modeling of the considered SoS using the same bond graph approach.

The structural proprties of the bond graph model are used to apply FDI on the physical CS in order to detect and isolate faults. Once, FDI procedure is applied on the bond graph models of the physical CSs, the reconfiguration strategy can be developed accordingly for the whole supervision of the SoS. In the next chapter, the proposed modeling approach is applied to an ITS.

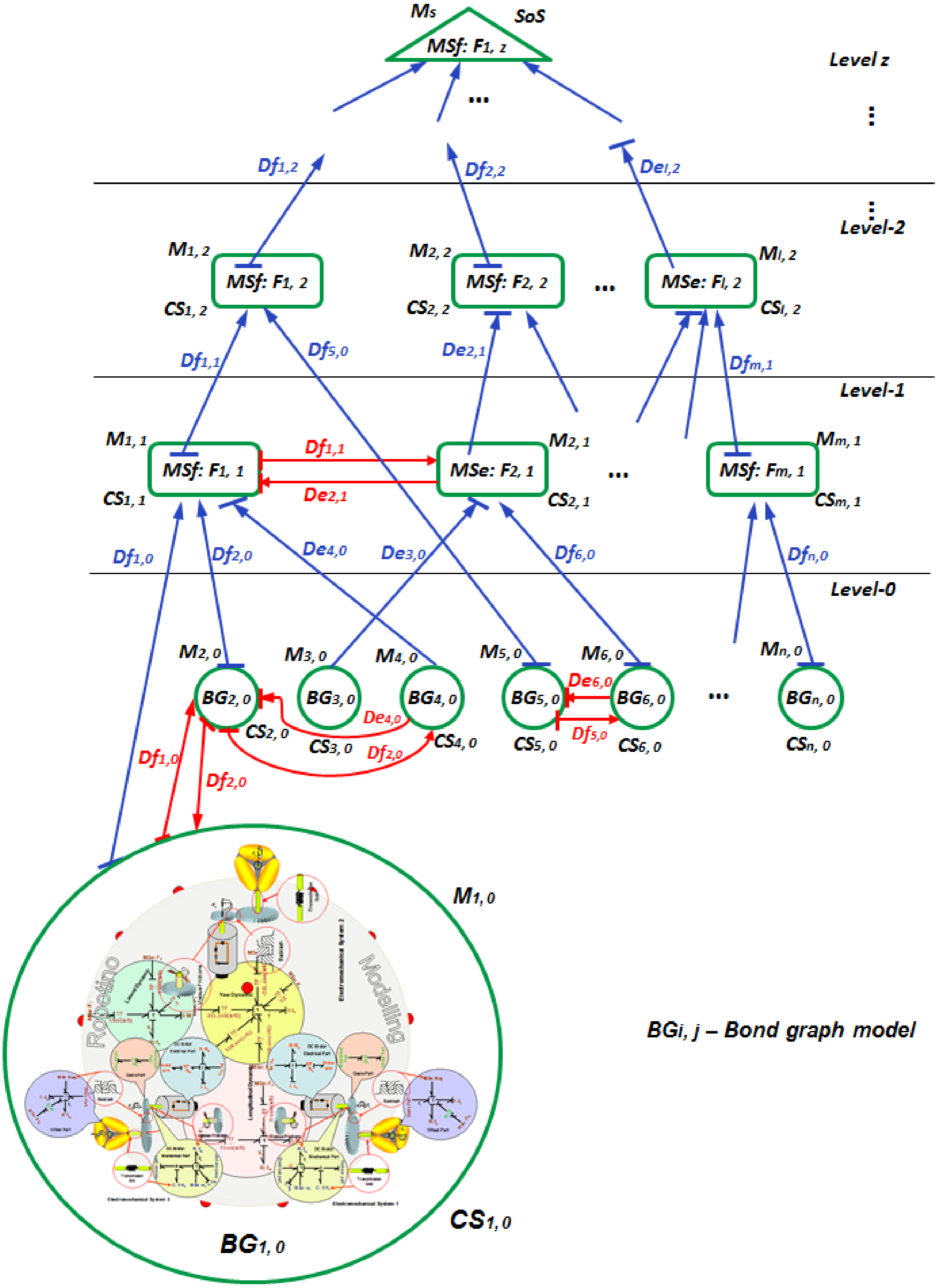


Figure 3.24: Multilevel bond graph model of a SoS.

4

Application: Modeling of ITS

4.1 Introduction

In the previous chapter, the bond graph modeling of a SoS is proposed. In this chapter, the proposed approach is applied to Intelligent transportation system (ITS). An ITS is consisted of intelligent vehicles, intelligent infrastructure, ICT tools, users, etc.; and it is applicable to any mode of transport namely road, rail, water, and air. In the present work, we focus on the road transport and SoS approach is applied to model an ITS considering the traffic of a platoon of Intelligent autonomous vehicles (IAVs).

Nowadays, management of road traffic is becoming more important to achieve the goal of sustainable transport as road transport is the dominant means of transport in EU-27 both for passengers and freight. In 2008, road transport accounted for 83% of total passenger transport and 46% of total goods transport. Road transport has increased significantly over years. From 2000 to 2008, the car ownership per 1000 inhabitants in the EU-27 grew by 13%. During the same period, total goods transport grew by 16.9% whereas freight traffic by road grew by 23.6%. These levels of growth imply significant increases in road traffic congestion and road transportation-related CO2 emissions. Road transport currently accounts for 70.9% of all transport related CO2 emissions in EU-27 (Psaraki et al. [2012]).

For sustainable transport, it is very important to achieve good traffic conditions on roads, which helps to reduce congestion and to achieve the smooth flow of traffic. Congested traffic leads to an increase in the cost of transport, pollution, accidents, and travel time. Traffic safety and operational problems are the major challenges in transportation within any country. In this respect, traffic management requires a clear understanding of the traffic flow operations. Here, we consider the traffic flow in ITS. An ITS helps in having smooth traffic flow on roads, moreover, it can be a solution for space optimization problem in a confined space like port terminal environment.

Traffic modeling and analysis enable to know the behavior of traffic flow and to predict the traffic conditions with changes in time. Traffic phenomena are unpredictable and complex, and are very difficult to model. Reliable traffic models are required for better traffic management and supervision. A good traffic model can result in better prediction of the traffic behavior, which can improve the traffic flow, and better operational efficiency.

As described in chapter 2, the traffic flow models can be classified according to the level of details with which they represent the traffic system. Thus, the traffic models can be categorized into four types: submicroscopic, microscopic, mesoscopic, and macroscopic level models.

In this work, we mainly focus on developing submicroscopic and microscopic level models and then use these models to deduce macroscopic model variables (average speed, density, and flow). We do not consider mesoscopic level model. Finally, all the three levels are combined to develop a multilevel model of the traffic dynamic in ITS.

4.2 Problem formulation

Based on the literature review of traffic modeling in chapter 2, the following gaps are identified:

- Most of the existing traffic models are either microscopic or macroscopic levels models.

- A multilevel model of traffic is required to handle the problems such as, if there is a fault in a vehicle in traffic at micro level, how this faulty vehicle affects the whole traffic at macro level.

- In addition, it is very difficult to calculate the energy consumption in the traffic flow with micro or macro model alone.

In the present work, a generic approach for modeling of the traffic dynamic is proposed, which combines both the modeling approaches based on microscopic and macroscopic levels of details. In addition, we model the traffic on the submicroscopic level, which is still not considered in most of the traffic models. Submicroscopic modeling of traffic is very important to describe the effect of the dynamics of an individual vehicle on the traffic. In submicroscopic modeling, we can consider the longitudinal, lateral, yaw, and actuator dynamics for each vehicle. The benefits of adding submicroscopic model can be given as follows:

- The effect of the individual vehicle's dynamics can be described on the whole traffic flow.
- Heterogeneous vehicles can be modeled with different properties.
- Faults in vehicles (e.g., failure of the actuator) can be identified and can take corrective action.

Our main aim in this chapter is to provide a generic multilevel traffic dynamic model, which couples three modeling approaches.

- Submicroscopic model: longitudinal, lateral, yaw, and actuator dynamics of each vehicle.
- Microscopic model: behavior of the follower vehicle in response to the motion of the leader vehicle to it.
- Macroscopic model: whole traffic flow with average values of traffic variable.

This generic multilevel model of traffic is developed using the bond graph modeling technique. The characteristics of the bond graph modeling approach can be summarized as follows.

- The bond graph modeling is based on the power transfer principle between the different elements of a system.
- The bond graph approach is very powerful to model in a unified way the physical systems of various natures independently of the considered domain (mechanical, electrical, thermal, etc.).

- The mathematical equations (differential equations) can be systematically derived from the bond graph model.

- The causal and structural properties of bond graph allow to apply control and supervision strategies.

- A bond graph model enables understanding the dynamic behavior of the process with a graphical vision.

- It is a modular modeling approach and it is possible to add/remove many dynamics of a system.

4.3 Bond graph modeling of ITS

The concept of SoS can be applied in the field of transportation as described in chapter 2. Hence, the proposed approach for SoS modeling can be applied to the traffic dynamic modeling in ITS consisting of a platoon of IAVs. Such set of vehicles can describe an organization of SoS, because each elementary component system is operationally and managerially independant; they are dispatched geographically, with a continuous exchange of information; finally they can structurally make a self-reconfiguration of their organization. Figure 4.1 shows multi-level representation of the traffic dynamic in ITS.

Refer to Figure 4.1, three levels of the road traffic dynamic namely submicroscopic, microscopic and macroscopic (Tampere and Arem [2001]) are presented in line with the levels of a SoS.

- Submicroscopic level describes the physical models of IAVs considering their different dynamics like longitudinal, lateral, yaw, actuator, and steering dynamic. The submicroscopic variables include current in actuator, slip speed, angular speed of wheel, etc.

  Submicroscopic level represents the level-0 of the SoS which consists of physical CSs. Here, the physical CSs are 'i' number of IAVs denoted by $IAV_{i,0}$, and each IAV is assigned with a mission $M_{i,0}$.

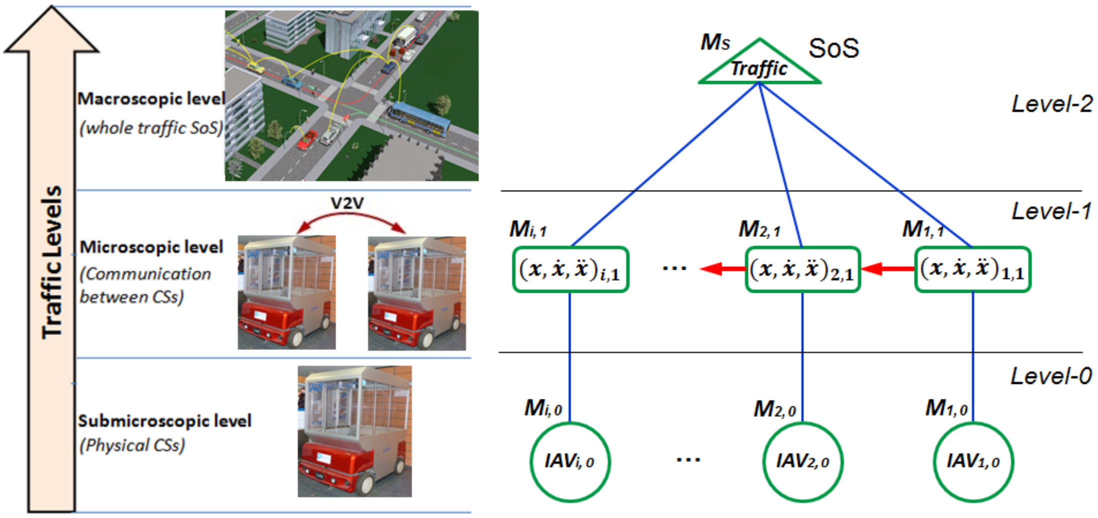


Figure 4.1: Multilevel representation of the traffic dynamic in ITS.

- Microscopic level describes the interaction between IAVs based on the car-following model. The car-following model describes the motion of a follower vehicle in response to the motion of its leader vehicle, and based on this interaction, the microscopic variables (position x, speed $\dot{x}$, and acceleration $\ddot{x}$) are calculated for each IAV.

  Microscopic level represents the level-1 of the SoS which consists of non-physical organizational CSs. Here, these CSs are formed based on information from the dynamic models of each IAV, and are denoted by $(x, \dot{x}, \ddot{x})_{i,0}$. Each CS is an organization of one IAV because at microscopic level individual IAVs are considered, and each CS is assigned with a mission $M_{i,1}$. At this level, information exchanges (V2V communication) between IAVs are modeled.

- Macroscopic level describes the whole traffic dynamic without distinguishing its constituent systems, and considers average values of variables. The macroscopic variables include mean speed, flow, and density of traffic.

  Macroscopic level represents the level-2 of the SoS, which is the highest level representing the SoS. Here, this SoS is formed based on the information from CSs at the level-1, and is denoted by *Traffic*. The SoS is an organization of all CSs at the level-1, and is assigned with a global mission M_s.

In this way, for modeling this traffic SoS, the following assumptions are considered.

- ITS is modeled considering the traffic dynamic in a platoon of IAVs.
- Three abstraction levels of the traffic dynamic are considered namely submicroscopic, microscopic, and macroscopic.
- Communication between IAVs is modeled assuming no communication delay.

In the following subsections, multilevel model of the traffic dynamic is developed step by step from the submicroscopic model of a road vehicle to microscopic model and, finally, the macroscopic model. Then, these models are combined to develop a multilevel model of the traffic dynamic. The model is developed using a single modeling approach bond graph.

4.3.1 Submicroscopic modeling

At the submicroscopic level, a two-dimensional model of an IAV named RobuCar is developed (Figure 4.2) considering the longitudinal and lateral motions of the vehicle in the X-Y plane, as shown in Figure 4.3. RobuCar is powered by batteries. The weight and polar moment of inertia of RobuCar are $390Kg$ and $160Kg.m^2$, respectively. The dimensions of RobuCar corresponding to Figure 4.3 are $a = 0.96m$, $b = 0.88m$, and $c = 0.65m$.

The considered IAV has four traction wheels, which are independently actuated with direct current (dc) motors. The IAV has two steering system, one for the two front wheels and another one for the two rear wheels. The IAV is equipped with an inertial sensor to measure its longitudinal, lateral, and yaw speeds. In addition, sensors are mounted to measure the angular speed of each wheel and the current drawn by each motor. The IAV is mounted with a laser rangefinder on its front bumper for tracking in a platoon based on interdistance measured from the laser. An on-board computer and electronic circuitry on RobuCar allow intelligent tracking in a platoon by integrating the proposed model in on-board computer.

Figure 4.2: IAV (RobuCar) at LAGIS.

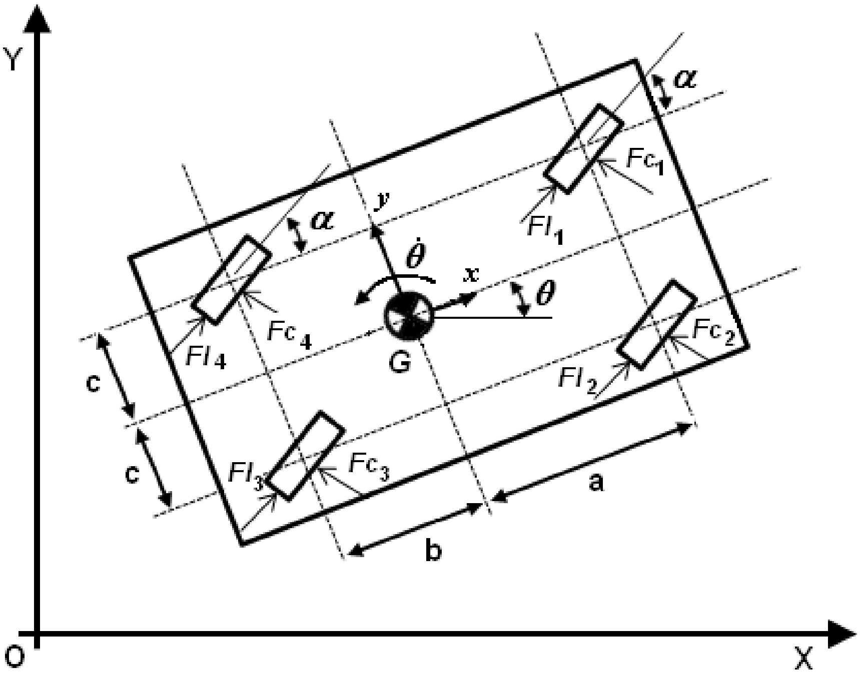


Figure 4.3: Schematic of the vehicle.

In Figure 4.3, the schematic top view of an IAV is shown, in which x-y is the body fixed frame and X-Y is the inertial frame. The orientation of the x axis with respect to the X axis is given by θ. The dimensions of the vehicle are denoted by a, b, and c, whereas G represents the centre of mass (CM) of the vehicle to which

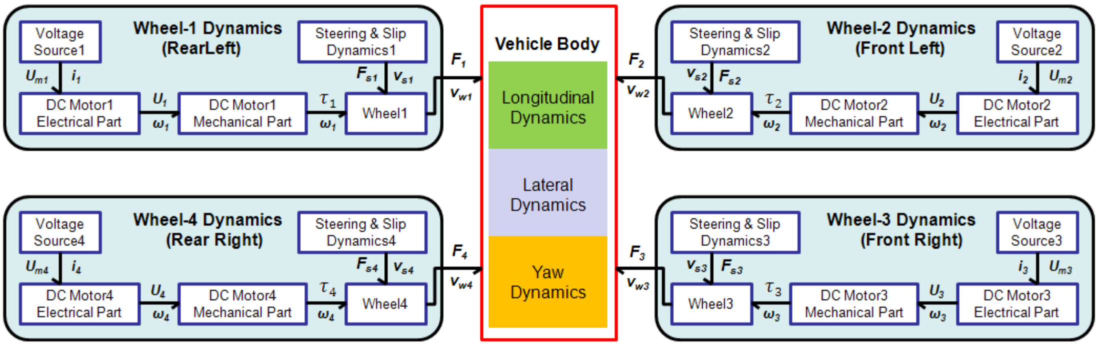


Figure 4.4: Word bond graph of the vehicle.

the x-y frame is fixed. Angle α denotes the steering angle of the wheel. F_{lj} and F_{cj} (where j is wheel number =1, 2, 3 or 4) denote the longitudinal force and the cornering force transmitted to the wheel, respectively.

An IAV is a very complex system and is composed of various dynamics. In our approach, the number of considered dynamics is not very important because we are building a generic multilevel model and the bond graph is a modular modeling tool, in which we can add or remove the different dynamics. The following modeling assumptions are made: 1) the IAV moves in a plane surface; 2) the road is uniform and the suspension, roll, and pitch dynamics are not considered; 3) each wheel is independently driven by the dc motor; and 4) all the wheels are steerable.

Finally, the following dynamics are considered: 1) traction actuator, slip, and steering dynamics of the wheel and 2) longitudinal, lateral, and yaw dynamics of the vehicle body (CM). The word bond graph for the considered dynamics of the vehicle is shown in Figure 4.4.

Refer to Figure 4.4, in the wheel j dynamics part, voltage source provides voltage U_{mj} and current i_j to the electrical part of the motor, which gives output (voltage U_j) to the mechanical part of the motor. The output of the motor (torque τ_j and angular speed ω_j) and the effect of steering and slip dynamics (force F_{sj} and slip velocity v_{sj}) generate wheel velocity v_{wj} and force F_j, which are transmitted to the vehicle body (CM). The dynamics of the four wheels generate longitudinal, lateral and yaw dynamics of the vehicle body. Pathak et al. [2008] and Loureiro et al. [2012] developed the dynamic model of an IAV using the bond graph technique.

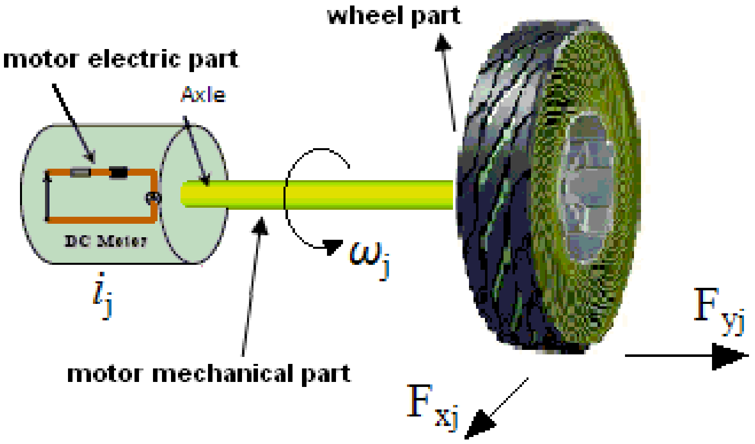


Figure 4.5: Considered scheme of the j^{th} motor and wheel system.

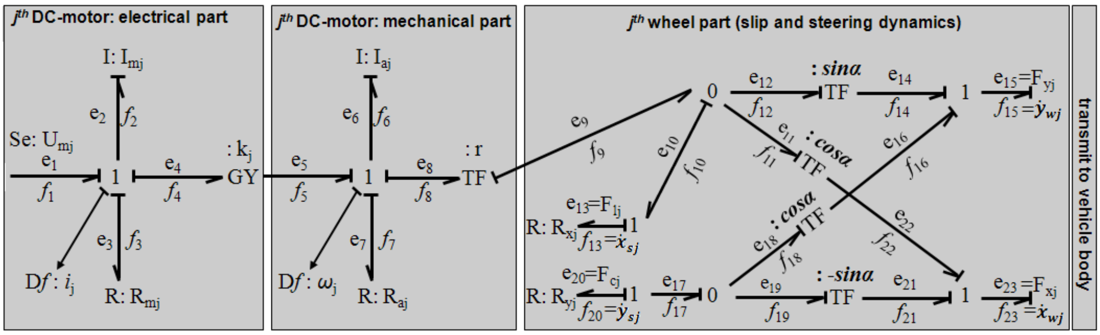


Figure 4.6: Bond graph model of the motor and wheel dynamics.

The IAV is composed of four independent quarters of IAV (wheel 1, wheel 2, wheel 3 and wheel 4). Let us start with the dynamics of wheel j (j=1, 2, 3 and 4). Figure 4.5 shows the considered scheme of the motor and wheel system. The corresponding bond graph model of the wheel j dynamics is shown in Figure 4.6. In the electrical part of the motor, U_{mj}, I_{mj}, R_{mj} and k_j represent the voltage, inductance, resistance and torque constant of the motor, respectively. In the mechanical part of the motor, I_{aj} and R_{aj} represent the polar moment of inertia and friction of the wheel axle, respectively. Angle α is the steering angle and r is the radius of the wheel. R_{xj} and R_{yj} represent the slip contribution in x- and y-directions, respectively. The full-headed arrows corresponding to current i_j in motor and angular speed of the wheel axle ω_j represent the sensors to measure the value of the corresponding parameter.

The dynamic equations of the system are systematically deduced from the bond graph model in Figure 4.6, in which e_n and f_n are the effort and flow in the corresponding bond number n (n=1, 2, 3...). The equations are deduced as follows.

i) Two system states:

$$p_{mj} = \int e_2; \qquad p_{aj} = \int e_6$$

ii) Junction structural equations:

$$\begin{array}{l}
1-junction\begin{cases} f_1 = f_2 = f_3 = f_4 = i_j = \frac{p_{mj}}{I_{mj}} \\ e_1 - e_2 - e_3 - e_4 = 0 \end{cases} \\
1-junction\begin{cases} f_5 = f_6 = f_7 = f_8 = \omega_j = \frac{p_{aj}}{I_{aj}} \\ e_5 - e_6 - e_7 - e_8 = 0 \end{cases} \\
1-junction\{f_{10} = f_{13} = \dot{x}_{sj}; \qquad e_{10} - e_{13} = 0 \\
1-junction\{f_{17} = f_{20} = \dot{y}_{sj}; \qquad e_{17} - e_{20} = 0 \\
0-junction\begin{cases} e_9 = e_{10} = e_{11} = e_{12} = e_{13} = F_{lj} \\ f_9 - f_{10} - f_{11} - f_{12} = 0 \end{cases} \\
0-junction\begin{cases} e_{17} = e_{18} = e_{19} = e_{20} = F_{cj} \\ f_{17} - f_{18} - f_{19} = 0 \end{cases} \\
1-junction\{f_{14} = f_{15} = f_{16} = \dot{y}_{wj};\ e_{14} - e_{15} + e_{16} = 0 \\
1-junction\{f_{21} = f_{22} = f_{23} = \dot{x}_{wj};\ e_{21} + e_{22} - e_{23} = 0
\end{array}$$

iii) Behavioral equations:

$$\begin{array}{l}
e_1 = U_{mj}; \qquad f_2 = \frac{1}{I_{mj}}\int e_2 \\
e_3 = R_{mj} f_3; \qquad e_4 = k_j f_5 \\
e_5 = k_j f_4; \qquad f_6 = \frac{1}{I_{aj}}\int e_6 \\
e_7 = R_{aj} f_7; \qquad e_8 = r e_9 \\
f_9 = r f_8; \qquad f_{11} = f_{22}\cos\alpha \\
f_{12} = f_{14}\sin\alpha; \qquad f_{18} = f_{16}\cos\alpha \\
f_{19} = -f_{21}\sin\alpha; \qquad e_{14} = e_{12}\sin\alpha \\
e_{16} = e_{18}\cos\alpha; \qquad e_{21} = -e_{19}\sin\alpha \\
e_{22} = e_{11}\cos\alpha
\end{array}$$

Based on the preceding equations; i) system states ii) junction structural equations and iii) behavioral equations, we can derive the iv) dynamic equations and the v) state-space representation of the system from the junction law corresponding to bonds 1,2,3,4 and bonds 5,6,7,8.

iv) Dynamic equations:

$$\dot{p}_{mj} = -\frac{R_{mj}}{I_{mj}}p_{mj} - \frac{k_j}{I_{aj}}p_{aj} + U_{mj}$$

$$\dot{p}_{aj} = \frac{k_j}{I_{mj}}p_{mj} - \frac{R_{aj}}{I_{aj}}p_{aj} - rF_{lj}$$

v) State-space representation of the system:

$$\overbrace{\begin{bmatrix} \dot{p}_{mj} \\ \dot{p}_{aj} \end{bmatrix}}^{\dot{p}} = \overbrace{\begin{bmatrix} -\frac{R_{mj}}{I_{mj}} & -\frac{k_j}{I_{aj}} \\ \frac{k_j}{I_{mj}} & -\frac{R_{aj}}{I_{aj}} \end{bmatrix}}^{A} \overbrace{\begin{bmatrix} p_{mj} \\ p_{aj} \end{bmatrix}}^{p} + \overbrace{\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}}^{B} \overbrace{\begin{bmatrix} U_{mj} \\ rF_{lj} \end{bmatrix}}^{u}$$

$$\overbrace{\begin{bmatrix} i_j \\ \omega_j \end{bmatrix}}^{q} = \overbrace{\begin{bmatrix} \frac{1}{I_{mj}} & 0 \\ 0 & \frac{1}{I_{aj}} \end{bmatrix}}^{C} \overbrace{\begin{bmatrix} p_{mj} \\ p_{aj} \end{bmatrix}}^{p}$$

The longitudinal and lateral speeds $\dot{x}_{wj}$ and $\dot{y}_{wj}$ of the wheel, respectively, in conjunction with the wheel's spinning speed generate the longitudinal and lateral slip speeds $\dot{x}_{sj}$ and $\dot{y}_{sj}$, respectively; and the dynamic relations can be derived from the junction law corresponding to bonds 9,10,11,12 and bonds 17,18,19 as given in

$$\dot{x}_{sj} = r\omega_j - \dot{x}_{wj}\cos\alpha - \dot{y}_{wj}\sin\alpha \tag{4.1}$$

$$\dot{y}_{sj} = -\dot{x}_{wj}\sin\alpha + \dot{y}_{wj}\cos\alpha \tag{4.2}$$

The longitudinal force F_{lj} and the cornering force F_{cj} are functions of the longitudinal and lateral slip speeds, respectively, and the dynamic equations can be derived from the junction law corresponding to bonds 10,13 and bonds 17,20 as given in

$$F_{lj} = R_{xj}\dot{x}_{sj} \tag{4.3}$$

$$F_{cj} = R_{yj}\dot{y}_{sj} \tag{4.4}$$

For a small value of slip and not considering the wheel camber, the values of R_{xj} and R_{yj} can be given as follows (Drozdz and Pacejka [1991]): $R_{xj} = \frac{C_x}{\dot{x}}$ and $R_{yj} = \frac{C_y}{\dot{x}}$. The coefficients C_x and C_y are dependent on vertical wheel load and $\dot{x}$ is the velocity of the CM of the vehicle in the x-direction. F_{xj} and F_{yj} are the forces generated by the wheel in x- and y-directions, respectively, and are transmitted to the body of the vehicle in the x- and y-directions, respectively; the equations can be derived from the junction law corresponding to bonds 14,15,16 and bonds 21,22,23 as given in

$$F_{xj} = F_{lj}\cos\alpha - F_{cj}\sin\alpha \tag{4.5}$$

$$F_{yj} = F_{lj}\sin\alpha - F_{cj}\cos\alpha \tag{4.6}$$

The complete bond graph model of the IAV considering all the dynamics is shown in Figure 4.7. Symbols m and J represent the mass and polar moment of inertia of the vehicle, respectively. The dimensions of the vehicle are denoted by a, b and c in modulus of transformer elements. The full-headed arrows corresponding to the speeds ($\dot{x}$, $\dot{y}$, $\dot{X}$, $\dot{Y}$ and $\dot{\theta}$) of the vehicle's CM represent the sensors to measure the value of the corresponding parameter.

In Figure 4.7, the longitudinal and lateral motions of the four wheels are transformed to the longitudinal, lateral, and angular motions of the vehicle body. The dynamic relations can be deduced from this bond graph. By applying junction law at the longitudinal, lateral, and yaw dynamics junctions, we get

$$m\ddot{x} = F_{x1} + F_{x2} + F_{x3} + F_{x4} + m\dot{\theta}\dot{y} \tag{4.7}$$

$$m\ddot{y} = F_{y1} + F_{y2} + F_{y3} + F_{y4} - m\dot{\theta}\dot{x} \tag{4.8}$$

$$J\ddot{\theta} = \left(F_{y1} + F_{y2}\right)a - \left(F_{y3} + F_{y4}\right)b - \left(F_{x1} - F_{x2} - F_{x3} + F_{x4}\right)c \tag{4.9}$$

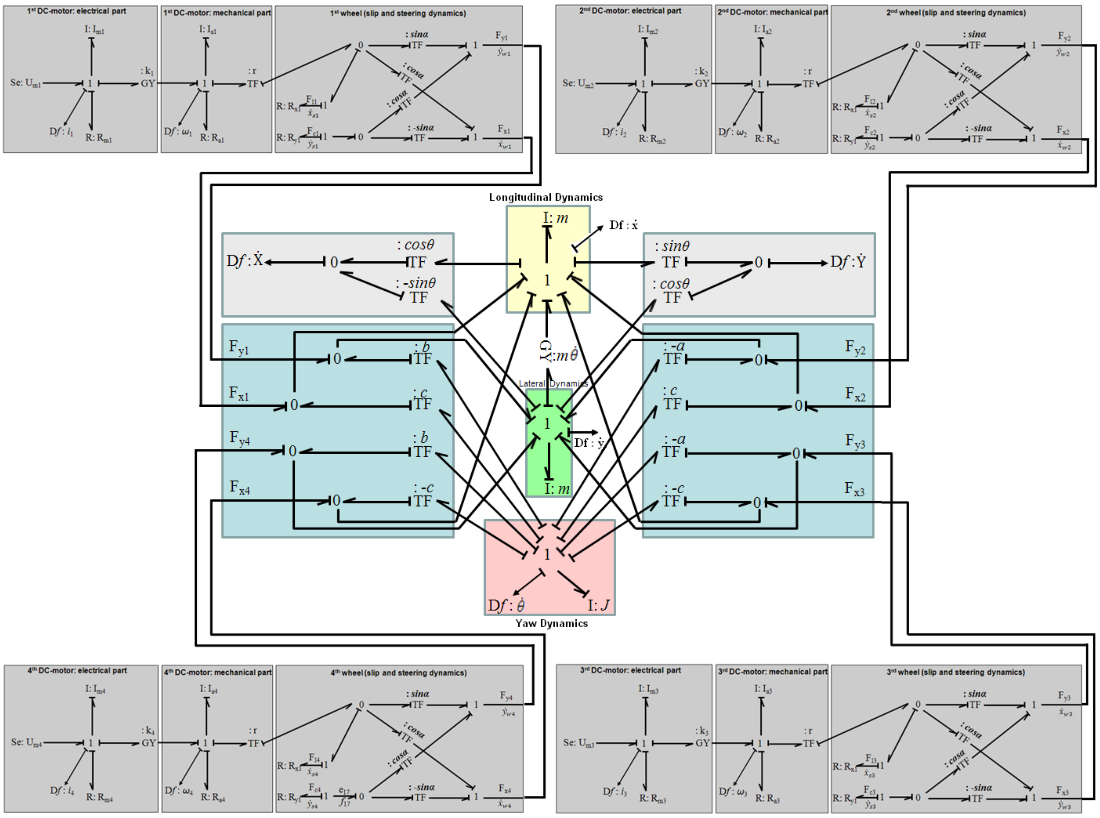


Figure 4.7: Complete bond graph model of the IAV.

The dynamic relations for the longitudinal, lateral, and yaw motions of the IAV are given by the equations 4.7, 4.8, and 4.9, respectively. The velocity of the CM in inertial frame X-Y is obtained by the transformation of x-y frame by angle θ.

The bond graph model of the IAV is encapsulated, as shown in Figure 4.8. In this way, now we have the complete two-dimensional dynamic model of a road vehicle.

4.3.2 Microscopic modeling

At the microscopic level of traffic dynamic, the interaction between the IAVs is observed. A microscopic model of traffic is a ‘car-following’ model, in which the leader vehicle influences the driving behavior of the follower vehicle, as shown in Figure 4.9.

Figure 4.8: Encapsulated bond graph dynamics of the IAV.

In Figure 4.9, the leader vehicle is n and the follower vehicle is $n+1$; x_n and x_{n+1} represent the positions of the leader and follower vehicles, respectively, with respect to a reference frame. L_n and L_{n+1} represent the lengths of the leader and follower vehicles, respectively. The relative motion of the follower vehicle depends on the motion of the leader vehicle, and follower vehicle always tries to maintain a minimum safe separation (interdistance) with the leader vehicle.

In our approach of modeling at the microscopic level, we model jerky dynamics also known as 'stick-slip motion' of the follower vehicle in response to the interdistance between the vehicles (Merzouki et al. [2013a]). This stick-slip phenomenon is mainly found on the relative motion issued from the contact between different rigid mechanisms. This jerky phenomenon is generated by the presence of certain flexibility in the contact and represents a succession of jumps and stops. In this jerky dynamic, when the interdistance reaches to a very small value, then the follower vehicle applies brakes, and when the interdistance increases, then the follower vehicle accelerates again. **This stick-slip motion of the vehicle can be used to represent the driving behavior of the driver of a manually driven vehicle or an autonomous vehicle in response to the motion of its leader vehicle.**

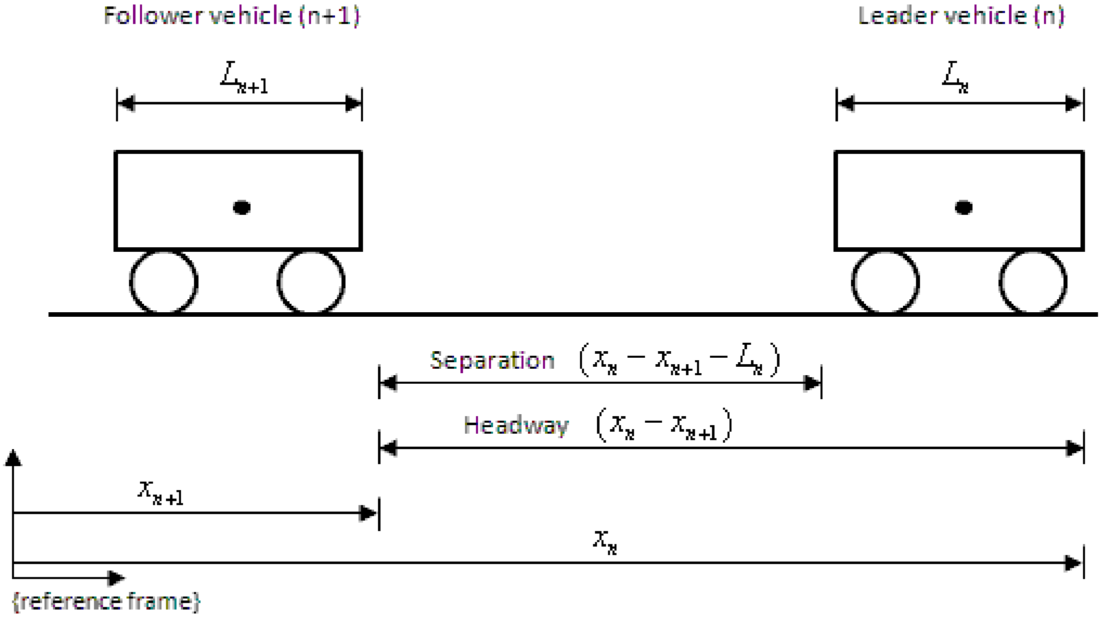


Figure 4.9: Car-following model.

In this work, the model of this stick-slip motion is developed based on interdistance as the physical connection between the vehicles. Actually, this physical connection is virtual, and we emulate this connection by the spring-dashpot system to represent the stick-slip motion, as shown in Figure 4.10. This virtual interconnection system represents in reality the state information of the interdistance variables, which is collected from the sensor's or driver's observation. In addition, this virtual interconnection system analytically describes the necessary effort calculated by the follower vehicle in order to maintain the safe interdistance, which depends on the values of stiffness of the spring and damping coefficient of the dashpot.

In Figure 4.10, we can see the platoon of i-IAVs (i=1,2,3...), which are virtually connected by the spring and the dashpot. The spring stiffness, damping coefficient, and position of the vehicles are denoted by k_i, b_i and x_i, respectively. The values of k_i and b_i depend on the driving behavior of the drivers in manually driven vehicles or type of information exchange in case of autonomous vehicles.

Let us consider the generic system of the leader (n^{th}) and follower ($n+1^{th}$) IAVs. The submicroscopic bond graph models of the two vehicles are connected by the bond graph model of the spring-dashpot system, this virtual interconnection

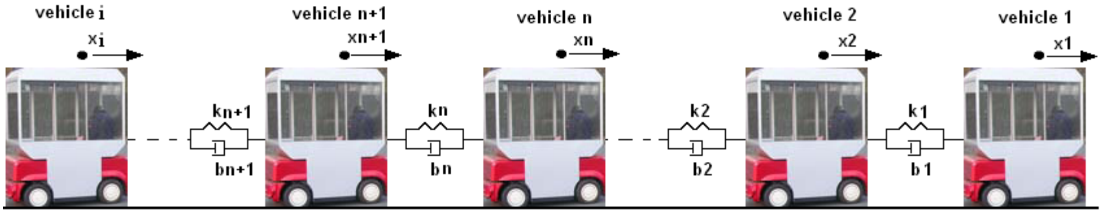


Figure 4.10: Platoon of IAVs virtually connected by the spring-dashpot system.

represents V2V wireless communication for platooning of IAVs (Figure 4.11). The microscopic bond graph model is shown in Figure 4.12.

Figure 4.11: Communication between IAVs.

In Figure 4.12, bonds 1 and 2 connect the spring-dashpot system to the longitudinal dynamic 1-junctions of the IAV(*n+1*) and IAV(n), respectively. The flow f_2 from the leader IAV(n) is transmitted to the virtual spring-dashpot system with a modulated source of flow MSf denoted by a full-headed arrow bond, which represents the flow activated bond and transfer only flow to the system and does not receive effort from the system; this restores the anisotropic property (motion of the leader vehicle is not affected by the motion of the follower vehicle) of the traffic flow. The effort e_1 from the spring-dashpot system is transmitted to the follower vehicle (*n+1*) to determine its flow f_1. The parameters k_n and b_n denote the spring stiffness and the damping coefficient, respectively, which are used to calculate the interdistance.

This interdistance model (spring-dashpot system) enables vehicle-to-vehicle (V2V) communication in the platoon. In fact, this interdistance model between

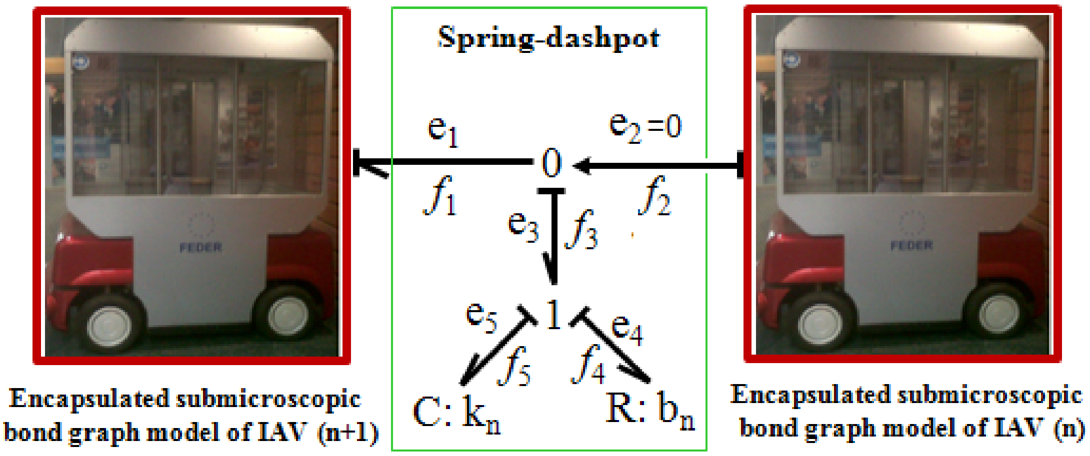


Figure 4.12: Microscopic bond graph model connects submicroscopic bond graphs of the leader and follower IAVs with a virtual bond graph model of the spring-dashpot system.

IAVs provides model-based control strategy for the local control of the platoon. This model-based control strategy analytically provides the calculation of necessary effort for the follower IAV to maintain safe interdistance with its leader IAV.

From the bond graph model shown in Figure 4.12, we can develop the control strategy for the local platoon control as shown in Figure 4.13.

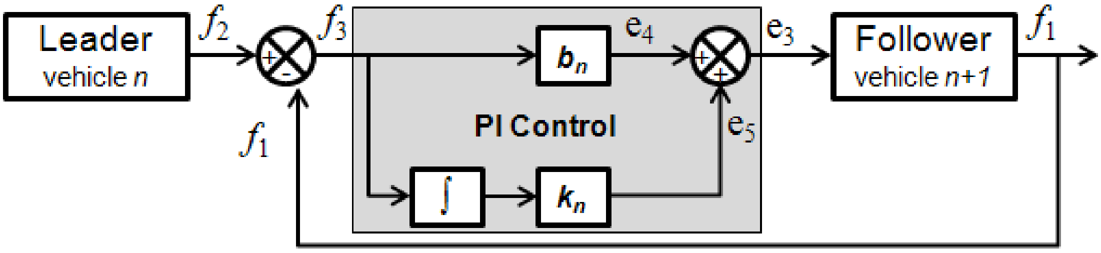


Figure 4.13: Platoon control strategy.

Refer to Figure 4.13, the first summation junction represents 0-junction corresponding to bonds 1, 2, and 3; and the second summation junction represents 1-junction corresponding to bonds 3, 4, and 5 of the bond graph model in Figure 4.12. At the first summation junction the difference of speeds of the leader and follower IAVs is taken as the error signal f_3. The proportional-integral (PI) control strategy is applied to compensate this error and to calculate the necessary effort e_3 to be applied on the follower IAV. The control equations can be given as follows.

Error in speed:

$$f_3 = f_2 - f_1 = \dot{x}_n - \dot{x}_{n+1} \tag{4.10}$$

Control effort applied on the follower vehicle:

$$e_3 = e_4 + e_5 = b_n(\dot{x}_n - \dot{x}_{n+1}) + k_n \int (\dot{x}_n - \dot{x}_{n+1}) \tag{4.11}$$

The voltages applied on the motors of the follower IAV *(n+1)* depend on this control effort e_3 to describe its controlled motion.

The dynamic relations for the microscopic traffic model can be derived from the bond graph shown in Figure 4.12. By applying the junction law corresponding to bonds 3, 4, 5, we get

$$\begin{aligned}
&e_3 = e_4 + e_5\\
&e_1 = e_3\\
&e_1 = m_{(n+1)}\ddot{x}_{(n+1)} - F_{x1(n+1)} - F_{x2(n+1)} - F_{x3(n+1)}\\
&\qquad - F_{x4(n+1)} - m_{(n+1)}\dot{\theta}_{(n+1)}\dot{y}_{(n+1)}\\
&\qquad\qquad\qquad\qquad\qquad\qquad \rightarrow \text{(from equation 4.7)}\\
&f_1 = \dot{x}_{(n+1)} \rightarrow [\text{longitudinal velocity of vehicle } (n+1)]\\
&e_2 = 0 \rightarrow \text{(no effort transfer because flow activated bond)}\\
&f_2 = \dot{x}_{(n)} \rightarrow [\text{longitudinal velocity of vehicle } (n)]\\
&e_4 = b_n f_4 = b_n f_3 = b_n(f_2 - f_1) = b_n(\dot{x}_{(n)} - \dot{x}_{(n+1)})\\
&e_5 = k_n \textstyle\int f_5 = k_n \int f_3 = k_n \int (f_2 - f_1)\\
&\quad = k_n \textstyle\int (\dot{x}_{(n)} - \dot{x}_{(n+1)})\\
&e_5 = k_n(\dot{x}_{(n)}t - x_{(n+1)})
\end{aligned}$$

Based on the preceding relations, the governing equation of the microscopic traffic dynamic can be given as

$$\begin{aligned}
m_{(n+1)}\ddot{x}_{(n+1)} + b_n(\dot{x}_{(n+1)} - \dot{x}_{(n)}) + k_n(x_{(n+1)} - \dot{x}_{(n)}t)\\
= F_{x1(n+1)} + F_{x2(n+1)} + F_{x3(n+1)} + F_{x4(n+1)} - m_{(n+1)}\dot{\theta}_{(n+1)}\dot{y}_{(n+1)}
\end{aligned} \tag{4.12}$$

In the preceding model equation (4.12), the acceleration response of the follower vehicle $\ddot{x}_{(n+1)}$ depends on the relative speed and distance between the vehicles as in equation (2.6) of the GHR model, but the proposed model is a more physical model and we consider the kinetics rather than the kinematics. The mass of the vehicle and the efforts from the actuators are taken into consideration. In addition, the GHR model ignores the vehicle types, but in the present model we can have different types of heterogeneous vehicles. In the proposed model, we can analyze the effect of the faulty vehicles on the traffic as we have the complete bond graph model of each vehicle.

From the microscopic bond graph model, we can get the values of microscopic variables (position, speed, and acceleration) for each vehicle at any instant of time. The position and speed of the vehicle (*n+1*) is shown in Figures 4.14(a) and (b), respectively, in response to the uniform motion of vehicle (*n*). It can be observed that the follower vehicle (*n+1*) decreases its speed when it comes closer to the leader vehicle (*n*), and, again, increases its speed when the separation is greater. This behavior represents the stick-slip motion.

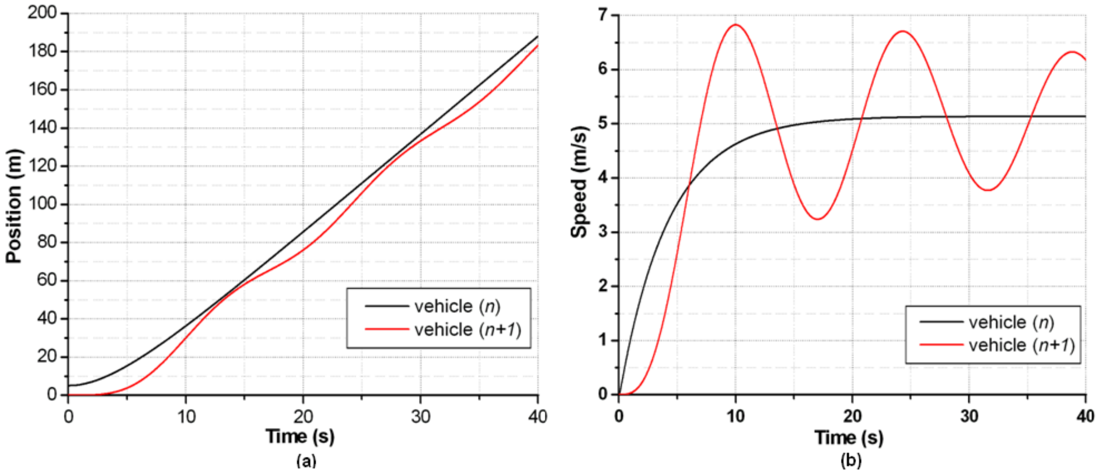


Figure 4.14: (a) Space-time and (b) speed-time behaviors of a platoon of two vehicles.

4.3.3 Macroscopic modeling

At the macroscopic level of traffic flow, the vehicles are not seen as separate entities and their aggregate effect is taken into consideration to calculate the average values of the macroscopic traffic variables (flow, density, and mean speed). The macroscopic traffic variables can be measured in two ways: measurement at a point or measurement along a length. Here, we deduce macroscopic variables from the bond graph model of microscopic model using the second method of measurement along a length, in which the measurements are taken by observing a section of the road for calculating the traffic variables. We analytically deduce density, flow, and mean speed as in the following (Gerlough and Huber [1975]).

1) Density: The density ρ of the traffic in a road section (for example length l) can be described as the number of vehicles per unit road length at any instant of time. If there are i vehicles in the road section under measurement at any instant of time, then density is given by

$$\rho = \frac{i}{l} \tag{4.13}$$

If, s_n is the distance headway for the n^{th} vehicle, which is given as $(X_n - X_{n+1})$, the state value of the position X_n of each vehicle is measured by the inertial sensor mounted on the vehicle. Here, we assume the distance headway from the CM of the leader vehicle to the CM of the follower vehicle; then, average distance headway can be given by

$$\overline{s} = \frac{1}{i}\sum_{n=1}^{i} s_n \tag{4.14}$$

The average density of traffic can be given in terms of average distance headway as

$$\rho = \frac{1}{\overline{s}} \tag{4.15}$$

2) Space Mean Speed: The space mean speed $\overline{v}$ is the average speed of the vehicles in a road section (for example, l) at any instant of time. If $\dot{X}_n$ is the speed of the n^{th} vehicle, which is measured by the flow sensor mounted on each vehicle, then the average of $\dot{X}_n$ gives space mean speed

$$\overline{v} = \frac{1}{i}\sum_{n=1}^{i} \dot{X}_n \tag{4.16}$$

3) Flow: The flow of traffic q is the number of vehicles passing through a point in the road section for a given interval of time. It is given by the vehicles per unit time at any point; thus, it is a point measurement and cannot be calculated using measurement along a length. However, flow can be calculated from the fundamental relation of traffic flow, i.e.,

$$q = \rho.\overline{v} \tag{4.17}$$

The speed $\dot{X}_n$ of the n^{th} vehicle is measured with the detector of flow (Df) and shown by the full-headed arrow in Figure 4.15. In addition, position X_n of the n^{th} vehicle is calculated by integrating speed $\dot{X}_n$. In this way, we can deduce the macroscopic variables of traffic flow from the microscopic bond graph model, which is developed from the submicroscopic model.

4.3.4 Multilevel modeling

Here, we propose a multilevel model of the traffic dynamic using a single modeling technique bond graph. The multilevel model of traffic SoS is composed of submicroscopic, microscopic, and macroscopic models of the traffic flow.

Let us consider a platoon of i number of IAVs moving on a road and following each other without passing. At the submicroscopic level, we have the bond graph model of each vehicle, which describes the dynamics of the vehicle, including the actuators. At the microscopic level, each vehicle moves based on the interdistance with the vehicle leading it, assuming V2V communication. At the macroscopic level, the aggregate behavior of the traffic is described. In this way, the multilevel bond graph model of the traffic dynamics is shown in Figure 4.15.

In Figure 4.15, the bond graph models of i vehicles are connected by the bond graph models of the virtual spring-dashpot system, as discussed in subsection 4.3.2. The modulated transformers *MSf* at the microscopic level represent the speeds of vehicles $\dot{X}_1$, $\dot{X}_2 ... \dot{X}_i$ with respect to inertial frame, based on the signals of flow (full-headed arrows *Df*) from each IAV. The speeds of the vehicles are integrated to get the positions X_1, $X_2 ... X_i$ of each vehicle.

At the macroscopic level, *MSf* represents the sum of the speeds of IAVs, based on the signals of flow *Df* from the modulated transformers *MSf* at the microscopic level. The full-headed arrows corresponding to the junctions $1_{\overline{v}}$ and 1_q are the sensors to measure the space mean speed and the flow of traffic, respectively. The modulus $1/i$ of the transformer *TF* represents the inverse of the number

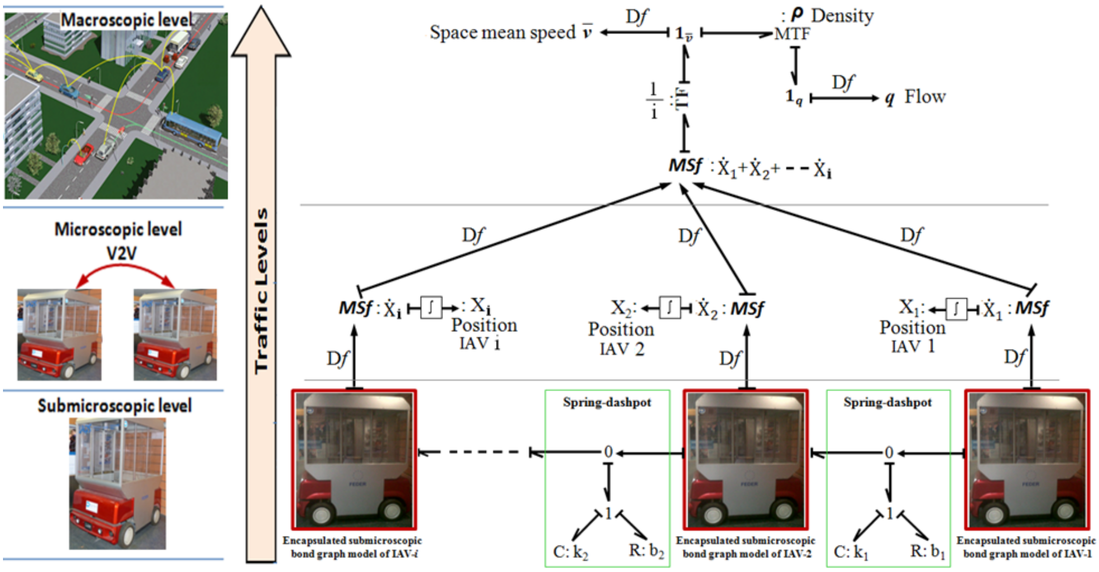


Figure 4.15: Multilevel bond graph model of the traffic dynamic SoS.

of vehicles. The modulus ρ of the modulated transformer MTF represents the density of the traffic and the value of ρ is calculated from the signals of positions in the bond graph, i.e.,

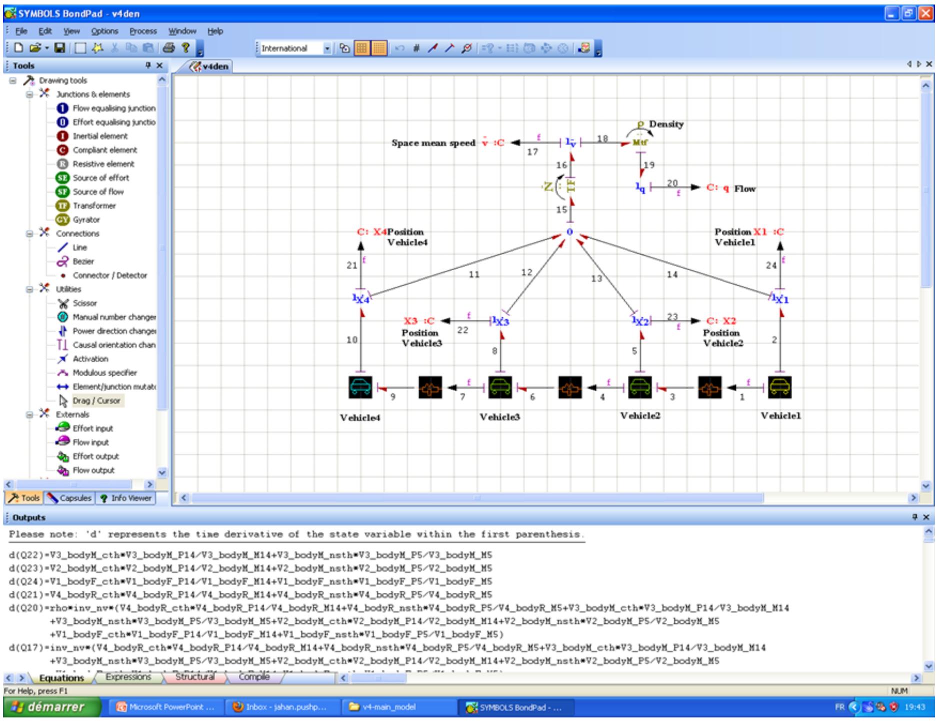
$$\rho = \frac{1}{\left((X_1 - X_2) + (X_2 - X_3) \ldots + (X_{i-1} - X_i)\right)/(i-1)} = \frac{1}{\bar{s}} \tag{4.18}$$

The inverse of density ρ represents the average distance headway $\bar{s}$ between the vehicles. From the bond graph in Figure 4.15, we can deduce the equations for the space mean speed $\bar{v}$ and flow q. By applying the junction law at the $1_{\bar{v}}$-*junction*, we get the following equation for the space mean speed $\bar{v}$ of the traffic:

$$\bar{v} = \frac{1}{i}(\dot{X}_1 + \dot{X}_2 \ldots + \dot{X}_i) \tag{4.19}$$

Now, we apply the junction law at the 1_q-*junction* and we get the following relation for flow q:

$$q = \rho\bar{v} \tag{4.20}$$



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Please note: 'd' represents the time derivative of the state variable within the first parenthesis.

d(Q22)=V3_bodyM_cth*V3_bodyM_P14/V3_bodyM_M14+V3_bodyM_nsth*V3_bodyM_P5/V3_bodyM_M5
d(Q23)=V2_bodyM_cth*V2_bodyM_P14/V2_bodyM_M14+V2_bodyM_nsth*V2_bodyM_P5/V2_bodyM_M5
d(Q24)=V1_bodyF_cth*V1_bodyF_P14/V1_bodyF_M14+V1_bodyF_nsth*V1_bodyF_P5/V1_bodyF_M5
d(Q21)=V4_bodyR_cth*V4_bodyR_P14/V4_bodyR_M14+V4_bodyR_nsth*V4_bodyR_P5/V4_bodyR_M5
d(Q20)=rho*inv_nv*(V4_bodyR_cth*V4_bodyR_P14/V4_bodyR_M14+V4_bodyR_nsth*V4_bodyR_P5/V4_bodyR_M5+V3_bodyM_cth*V3_bodyM_P14/V3_bodyM_M14
       +V3_bodyM_nsth*V3_bodyM_P5/V3_bodyM_M5+V2_bodyM_cth*V2_bodyM_P14/V2_bodyM_M14+V2_bodyM_nsth*V2_bodyM_P5/V2_bodyM_M5
       +V1_bodyF_cth*V1_bodyF_P14/V1_bodyF_M14+V1_bodyF_nsth*V1_bodyF_P5/V1_bodyF_M5)
d(Q17)=inv_nv*(V4_bodyR_cth*V4_bodyR_P14/V4_bodyR_M14+V4_bodyR_nsth*V4_bodyR_P5/V4_bodyR_M5+V3_bodyM_cth*V3_bodyM_P14/V3_bodyM_M14
       +V3_bodyM_nsth*V3_bodyM_P5/V3_bodyM_M5+V2_bodyM_cth*V2_bodyM_P14/V2_bodyM_M14+V2_bodyM_nsth*V2_bodyM_P5/V2_bodyM_M5
```

Figure 4.16: Simulation platform for SYMBOLS software package.

In this way, we have a generic multilevel model of the traffic SoS, which represents the submicroscopic, microscopic, and macroscopic variables using a single modeling technique bond graph.

4.4 Simulation results

For simulation purposes, we use Symbols Shakti software. SYMBOLS stands for **SY**stem **M**odeling by **BO**ndgraph **L**anguage and **S**imulation. It is a modeling, simulation, and control systems software for a variety of scientific and engineering applications. It automatically develops mathematical models and incorporates system nonlinearity and behaviors systematically. It supports activation, which is the facility to select the measurement and information transfer mode at modeling stages itself.

In addition, Symbols Shakti allows the modeler to create and incorporate subsystem modules called capsules in the model of bigger systems. These capsules can be used as a black box in any model. The model is solved using the Runge-

Kutta algorithm, which is a good general candidate for numerical solution of differential equations. We can set the value of error limit for the simulation in Symbols. In Figure 4.16, a screenshot of the software platform for Symbols is shown.

For simulation, a platoon of four IAVs is considered for two different scenarios. In the first scenario, the normal traffic operations are considered, in which four vehicles are moving on a road in a straight line. In the second scenario, one vehicle takes turn at an intersection and leaves the platoon.

4.4.1 First scenario

Let us consider a platoon of four vehicles moving on a road in straight line. The simulation results are shown in Figure 4.17. In Figure 4.17(a) and (b), the submicroscopic variables currents in the four motors of vehicle 1 and the angular speeds of the four wheels of vehicle 2 are plotted with respect to time, respectively. In Figure 4.17(c) and (d), the microscopic variables (position and speed) are plotted with respect to time; it can be seen that the leader (vehicle 1) is moving with a speed of $7.7 m/s$ and vehicle 2 follows it. It can be observed that vehicle 2 changes its speed with respect to time to maintain the separation with vehicle 1. For example, at time $8.5s$, when vehicle 2 comes very close to vehicle 1, its speed starts to decrease. Again, at time $13.8s$, when there is greater separation between the two vehicles, the speed of vehicle 2 starts to increase. In this way, this stick-slip motion allows maintaining a safe interdistance between the leader and follower vehicles. Similarly, vehicle 3 follows vehicle 2 and vehicle 4 follows vehicle 3 as shown in graph.

In Figure 4.17(e), the average distance headway between the vehicles is plotted with respect to time; it can be seen that there is a minimum average headway of $4.0m$ at time $11.0s$, when all the four vehicles are very close; but they still maintain a gap between them and do not hit at any point of time, as shown in Figure 4.17(c). In Figure 4.17 12(f)-(h), the macroscopic variables (mean speed, density, and flow) are plotted with respect to time; the mean speed of the traffic changes with respect to time as the speed of each vehicle in the traffic is changing to maintain a safe interdistance between the vehicles. The density of the traffic is also changing and its maximum ($246.9 veh/km$) when the average headway

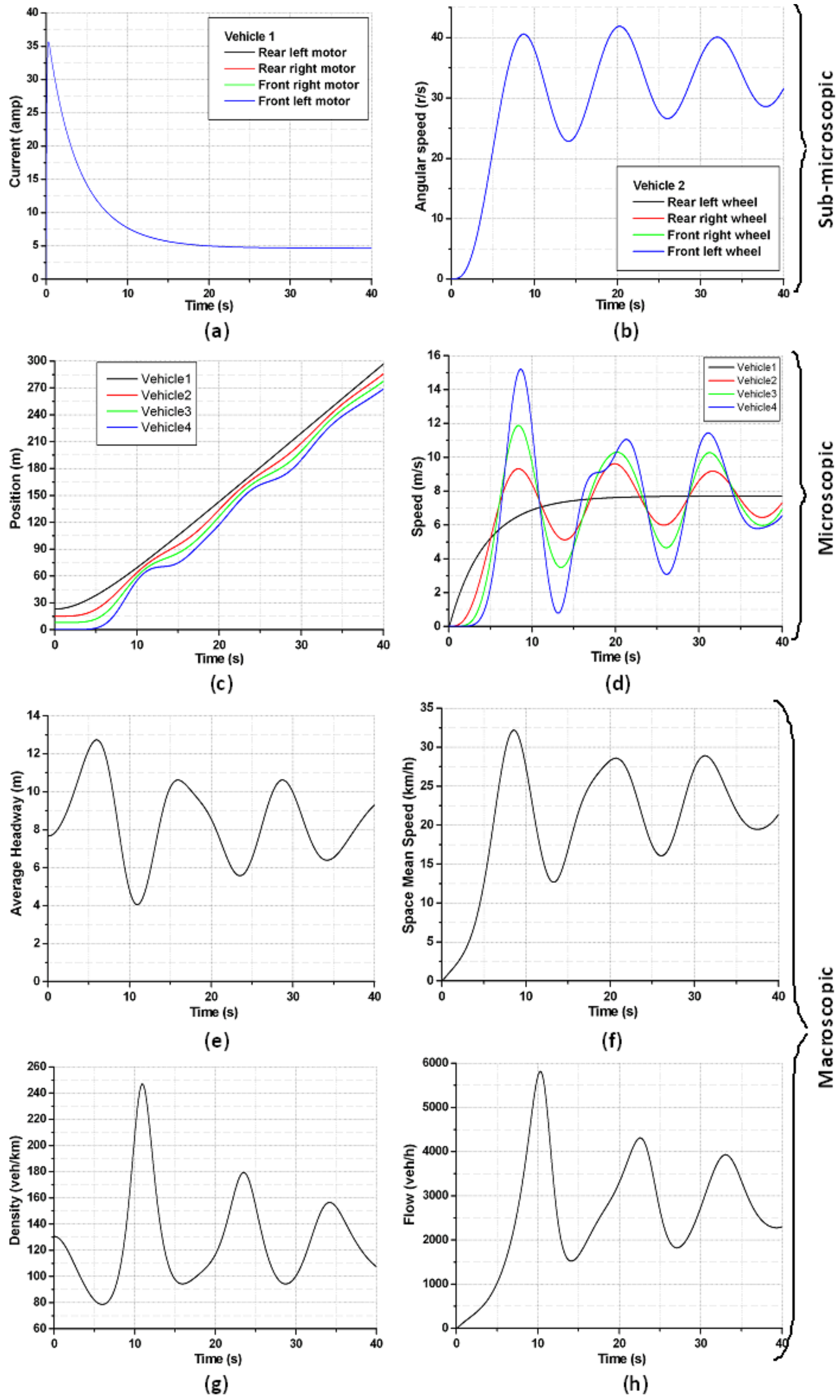


Figure 4.17: First scenario (normal traffic operation). (a) Current in each motor of vehicle 1. (b) Angular speed of each wheel of vehicle 2. (c) Position of each vehicle. (d) Speed of each vehicle. (e) Average distance headway between vehicles. (f) Space mean speed of the traffic. (g) Density of the traffic. (h) Flow of the traffic with respect to time.

is minimum at time $11.0s$, which represents the dense traffic, and vehicles are very close to each other. At time $10.3s$, flow of the traffic achieves its maximum value ($5812.1veh/h$); at this instant of time, the values of density ($228.4veh/km$) and mean speed ($25.4km/h$) can be called critical density and critical speed, respectively.

4.4.2 Second scenario

Let us consider a platoon of four vehicles moving on a road in a straight line; after some time, vehicle 2 takes a turn at an intersection on the road and leaves the platoon. To achieve this scenario, we removed the interconnection between vehicle 1 and vehicle 2, and vehicle 2 and vehicle 3 by putting the values of spring stiffness and damping coefficient equal to zero when vehicle 2 arrives at an intersection. In addition, at that moment of time, vehicle 1 is connected to vehicle 3, and vehicle 2 is steered by an angle (for example, $0.5rad$). The simulation results are shown in Figure 4.18. In Figure 4.18(a) and (b), the submicroscopic variables currents in the four motors of vehicle 1 and the angular speeds of the four wheels of vehicle 2 are plotted with respect to time, respectively. After $20s$, the angular speeds of the wheels of vehicle 2 start to decrease as they leave the platoon. In Figure 4.18(c) and (d), the microscopic variables (position and speed) are plotted with respect to time; it can be seen that the leader (vehicle 1) is moving with a speed of $7.7m/s$ and vehicle 2, vehicle 3, and vehicle 4 follow their leading vehicle as described in the previous simulation. However, at time $20s$, vehicle 2 takes a turn at an intersection and its speed in the x-direction starts to decrease and, finally, becomes zero. Now, it is no longer in the platoon.

In Figure 4.18(e), the average distance headway between the vehicles suddenly increases at time $20s$. In Figure 4.18(f)-(h), the macroscopic variables (mean speed, density, and flow) are plotted with respect to time. The behavior of the mean speed of the traffic is not much affected in this case compared with previous simulation. However, the density and the flow suddenly decrease at time $20s$ because one vehicle is removed from the platoon.

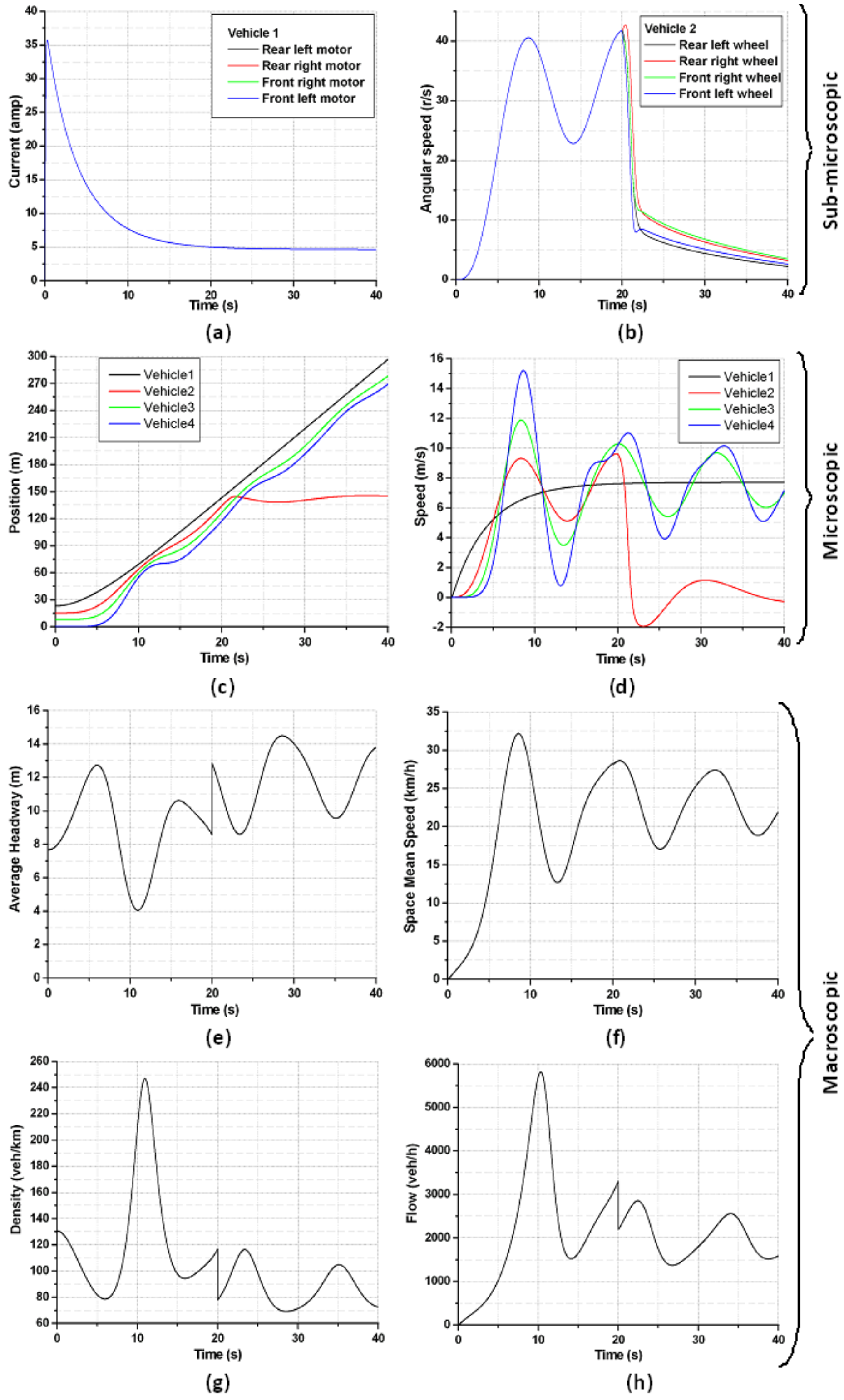


Figure 4.18: Second scenario (one vehicle leaves the platoon). (a) Current in each motor of vehicle 1. (b) Angular speed of each wheel of vehicle 2. (c) Position of each vehicle. (d) Speed of each vehicle. (e) Average distance headway between vehicles. (f) Space mean speed of the traffic. (g) Density of the traffic. (h) Flow of the traffic with respect to time.

4.5 Real-time simulation

For such simulation, we use professional software dedicated to engineering and research applications called SCANeR (Online [2014a]). It is a modular and real-time-based structure. The advantage of this simulation tool is that we can combine the submicroscopic, microscopic, and macroscopic models of the traffic. By using the application programming interface of Figure 4.19, it is useful to integrate the emulated interdistance model between the vehicles. The management of the real-time traffic flow is done through the association of the 3-D road mapping given in Extensible Markup Language format and the vehicle dynamics (see Figure 4.19). The main feature of such simulation tool in the framework of the InTraDE project (Online [2014b]) is to model a complex large-scale system describing a system of engineering systems for intelligent transport application.

Figure 4.19: Real-time simulation on SCANeR Studio software package.

For the following results, traffic of four heavy IAVs is involved with $m_i = 3500kg$ weight each, maximum speed of $25km/h$, a safe interdistance of $15m$, and interdistance model parameters of $b_i = 25N.s/m$ and $k_i = 0.1N/m$. It is assumed that the V2V communication is available using data information collected from the tracking process of the laser rangefinder. In this case, the follower vehicle tracks the target with adapted speed and interdistance, relative to the positioning

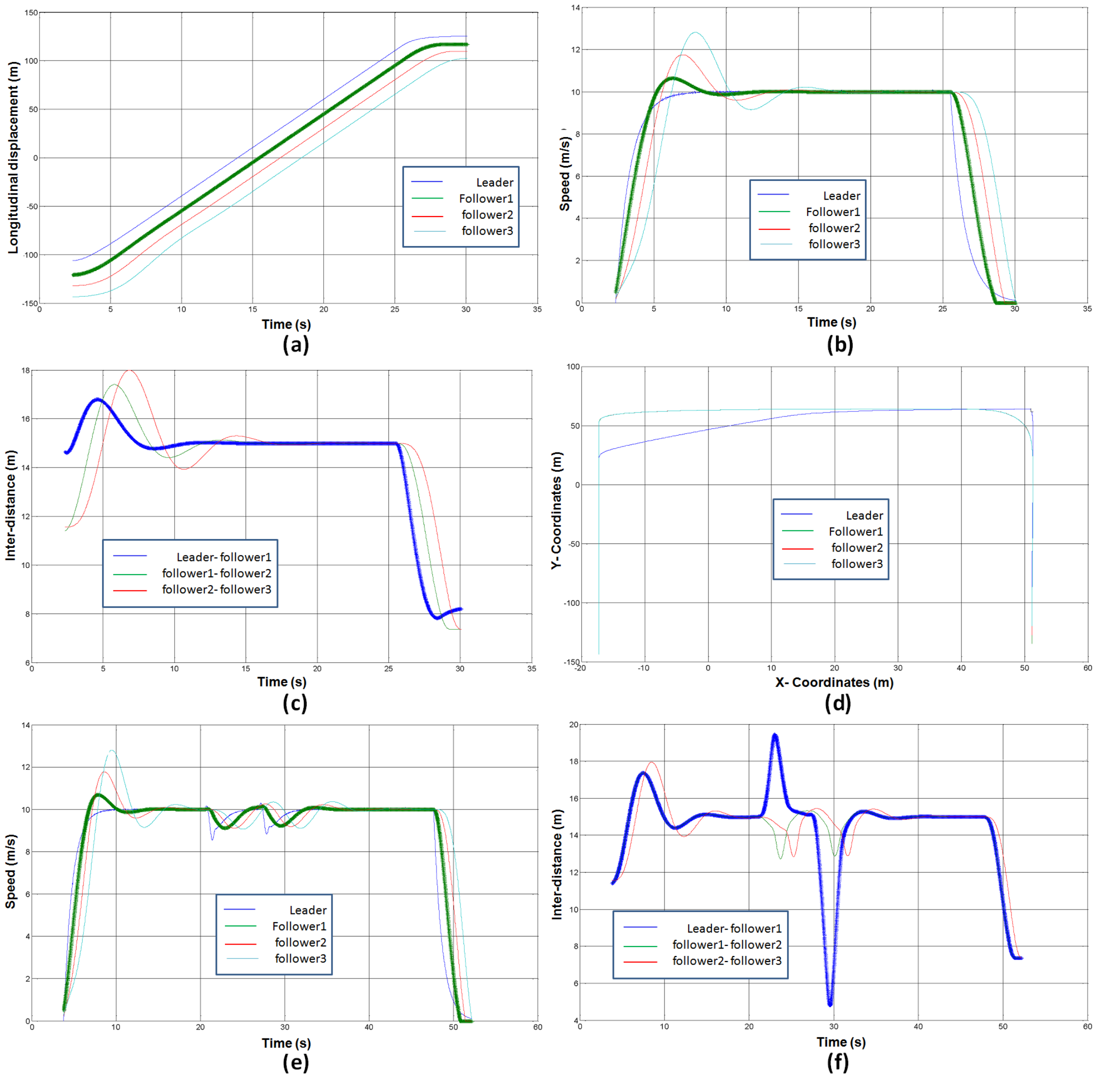


Figure 4.20: (a)-(c) Longitudinal tracking on a linear path, linear speeds of the IAVs, and interdistance profile between the platoon of vehicles for the first scenario, respectively. (d)-(f) Longitudinal tracking for a planar path, linear speeds of the IAVs, and interdistance profile between the platoon of vehicles for the second scenario, respectively.

and speed of its leader. Two scenarios are considered for this simulation. The first concerns a linear path tracking in Figure 4.20(a), where the traveled path of each vehicle is shown with respect to a uniform interdistance time at 2.5s. The profile of the linear speed for each vehicle in Figure 4.20(b) is divided into two periods, transient period with a variable damping behavior started from follower 1 until follower 4. This is due to the propagation of the jerky phenomenon on the platoon length. In the steady period, it is shown the uniformization of the tracking speed. The variation of the interdistance for each IAV is shown in Figure 4.20(c), with a visible stick-slip behavior during the transient period.

The second scenario shows a planar path in Figure 4.20(d), in which the longitudinal speeds and interdistances for the involved IAVs are presented in Figure 4.20(e) and (f), respectively, mentioning the transient and steady periods for each change of the path orientation.

4.6 Experimental results

We performed an experiment for the microscopic car-following model through an experimental platform. This platform is shown in Figure 4.21, in which there is a platoon of two IAVs; the first one is a light leader vehicle (RobuCar) with a mass of 400kg and the second one is a heavy follower vehicle (RobuRide) with a mass of 3000kg. The IAVs can detect their position and speed by sensors. The communication between the vehicles is established using a wireless connection with a central computer. The vehicles are equipped with laser rangefinder for the tracking.

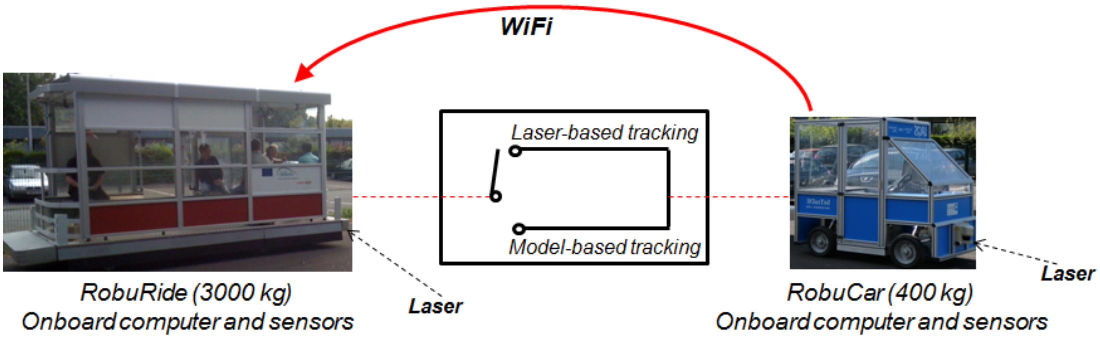


Figure 4.21: Experiment on a platoon of two IAVs.

The experiment is performed to test the proposed car-following model for tracking of IAVs in comparison with laser-based tracking of IAVs. We performed the test, first with laser rangefinder tracking and then tracking with the proposed model. The test is performed for 38s at a very low speed. In Figure 4.22, the black line curve represents the switch on/off of the proposed model. When it is 0, the model is not used and only laser-based tracking is performed, and when it

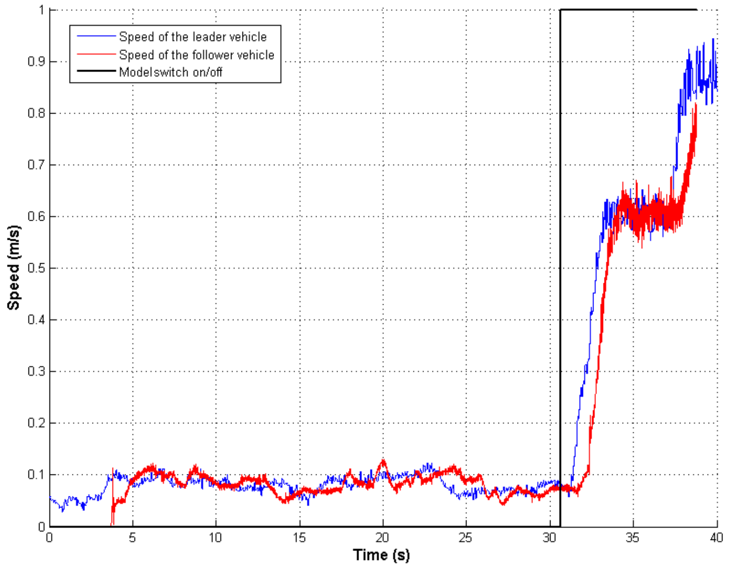


Figure 4.22: Speeds of the vehicles.

is 1, the proposed model is used for tracking. The profile of speeds of the leader and follower vehicles is shown in Figure 4.22 based on laser tracking before $31s$ and model-based tracking after $31s$.

In Figure 4.23, the red line curve shows the real interdistance between the vehicles measured from the laser rangefinder. The model is switched on after $31s$ and is used to estimate the interdistance, and it is represented by the blue line curve. We can see the deviation of estimated interdistance from the real interdistance in Figure 4.23. The difference between the interdistance estimated by the model and the interdistance measured by the laser can be observed in Figure 4.24. The maximum difference is $-10.3cm$ $(167 - 177.3 = -10.3cm)$ at $33s$, which causes an error of -5.8% maximum. This error may be because of the odometry precision and slip of the vehicles.

From the experimental results, we can conclude that the proposed model performs well with a maximum error of -5.8% in calculated interdistance by the model in comparison with real interdistance by the laser. Thus, the model can be used as an alternative for the tracking of IAVs in case of failure of the laser. The advantage of the proposed model in comparison with traditional models such as the GHR model is that the proposed model describes the kinetics of the vehicle rather than the kinematics and provides a model-based control of car-following

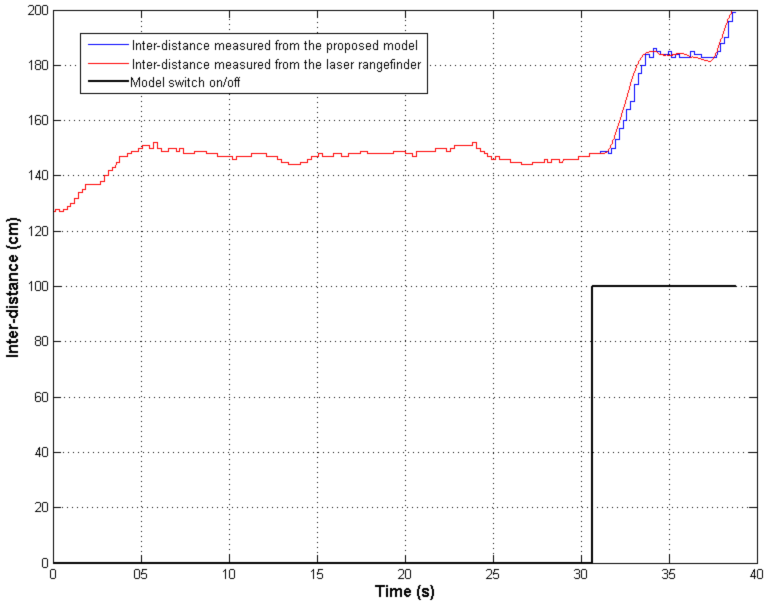


Figure 4.23: Interdistance between the vehicles.

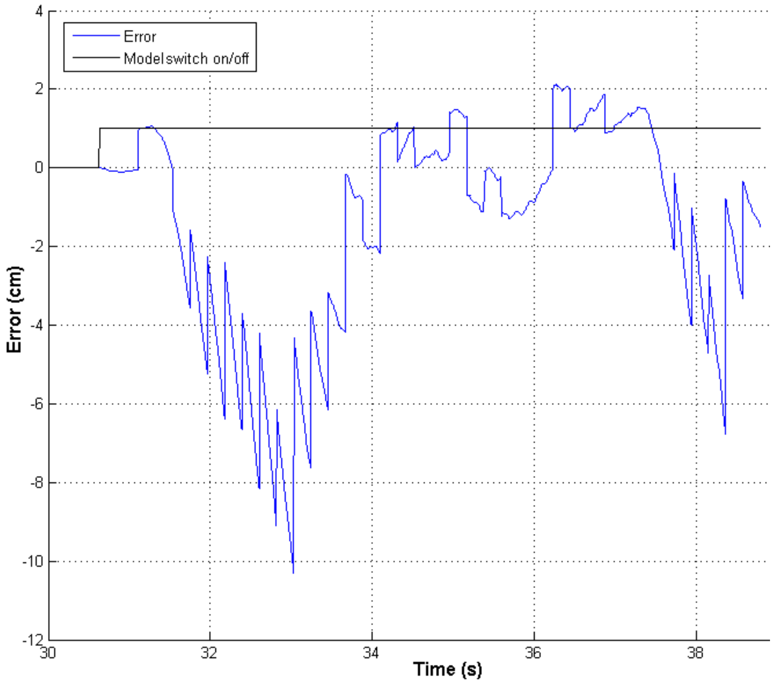


Figure 4.24: Error in interdistance.

behavior. In addition, we can model different types of vehicles such as heavy and light vehicles with their size and mass.

4.7 Summary of the chapter

In this chapter, a multilevel model of the traffic dynamic in ITS is developed, which combines submicroscopic, microscopic, and macroscopic level models of the traffic dynamic. All the levels of traffic SoS are modeled using the bond graph modeling approach, which provides graphical comprehension of the system. At the submicroscopic level, the dynamic bond graph model of a four-wheeled electric vehicle is developed and then, at the microscopic level, the car-following model is developed based on virtual interconnection between the submicroscopic models. At the macroscopic level, the macroscopic variables (average speed, density, and flow) are deduced from the submicroscopic and microscopic models. The simulation results show the stick-slip behavior of the interdistance between the vehicles, which represents the driving behavior in a platoon. The major benefits of the current model, as compared with the traditional models, are given in Table 4.1.

Table 4.1: Comparison of the proposed model with the existing models

Existing models	**Proposed model**
Either microscopic level or macroscopic level model.	Multilevel model and aggregates microscopic, macroscopic and submicroscopic levels.
The whole supervision of traffic is difficult.	Multilevel model allows the whole supervision of the traffic, also can identify the faulty vehicles at submicroscopic level.
The calculation of energy consumption in the vehicles is difficult.	Energy based model and can be used to calculate the energy consumption in each vehicle.
Most of the traditional car-following models are kinematics models and ignore the vehicle type.	The proposed model considers kinetics model and different types of heterogeneous vehicles can be modeled according to their mass and size.

Finally, the real-time simulation is performed for a platoon of four vehicles using a professional software package, i.e., SCANeR. In addition, the experiments on IAVs are performed to validate the model. The proposed multilevel bond graph model can be used for supervision of ITS. Thus, in the next chapter, the supervision of ITS is described based on the bond graph model.

5

Application: Supervision of ITS

5.1 Introduction

In the previous chapter, multilevel model of the road traffic dynamic is developed as a SoS. In the current chapter, this multilevel model is used for supervision of ITS considering a platoon of IAVs.

Supervision can be defined as the set of tools and methods used to operate a system/process in normal situation as well as in the presence of failures or undesired disturbances. The activities concerned with the supervision are the Fault Detection and Isolation (FDI) in the diagnosis level, and the Fault Tolerant Control (FTC) through necessary reconfiguration, whenever possible, in the fault accomodation level (Figure 5.1).

The bond graph approach allows model-based supervision of the considered system. The causal and structural properties of bond graph can be exploited for FDI and reconfiguration of a system in case of faulty situations.

In this chapter, the proposed multilevel bond graph model of the traffic SoS is used for supervision purpose. The FDI methods are applied to detect and isolate

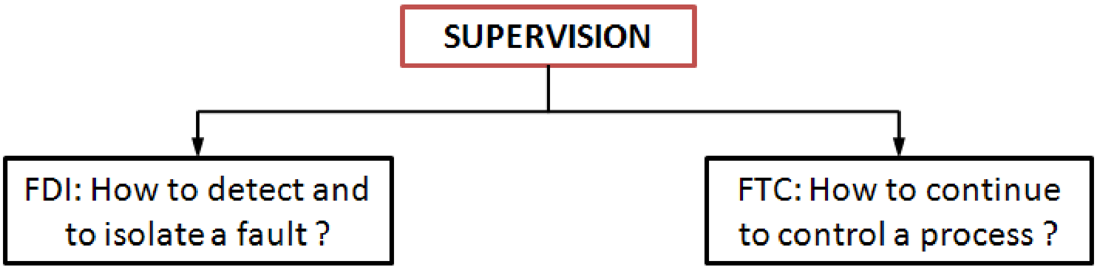


Figure 5.1: Supervision activities.

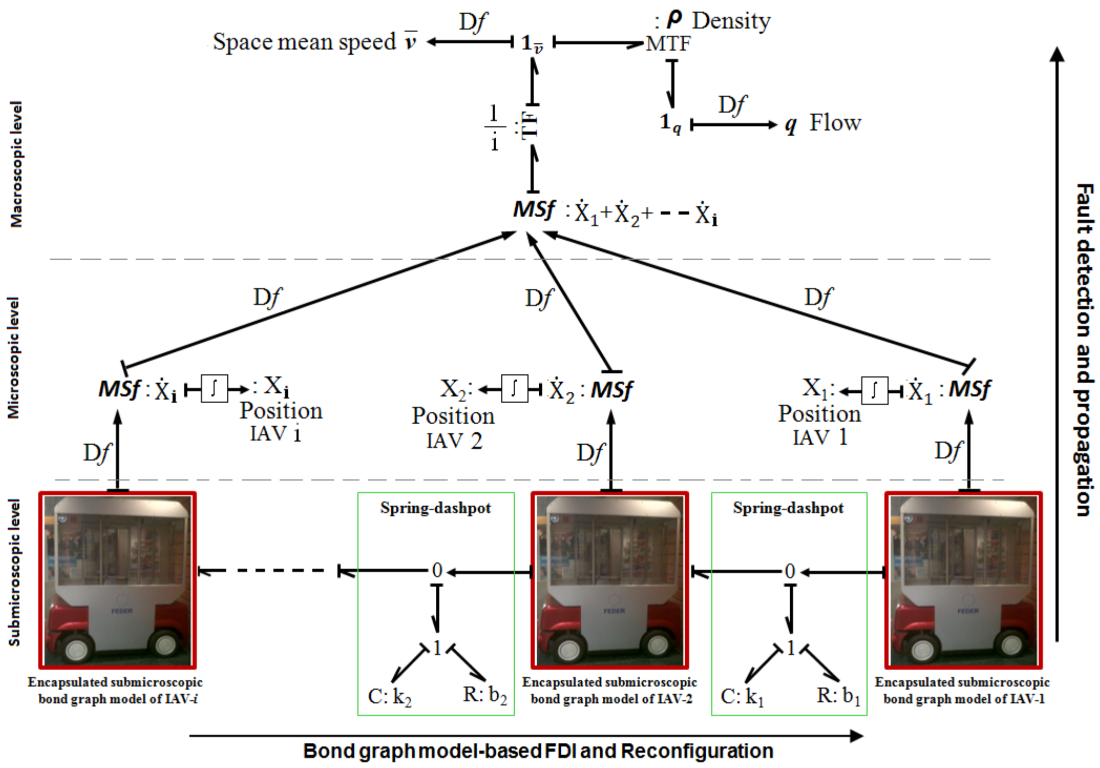


Figure 5.2: Multilevel bond graph model for supervision.

the faults at the submicroscopic level, and to evaluate the effect of these faults at the higher levels. Finally, a multilevel reconfiguration strategy is proposed to recover the platoon from the faults and to continue for achieving its global mission.

5.2 Multilevel model for supervision

Here, the same multilevel bond graph model is used for supervision of ITS as developed in the previous chapter. The model is shown in Figure 5.2.

Refer to Figure 5.2, the multilevel model is used for fault detection and to evaluate the effect of faulty physical component systems propagating from the lower level to the higher levels. The FDI methods are required to be applied at the submicroscopic level model in order to detect and isolate the faults in the IAVs. These faults may propagate to the microscopic and macroscopic level, which may lead to failure of the global mission of the multilevel model. A multilevel reconfiguration strategy is required to recover this SoS from the faulty situation to the normal situation.

In the following sections, the FDI methods and the multilevel reconfiguration strategy are described for the proposed mulilevel bond graph model of the traffic dynamic.

5.3 Fault detection and isolation

The bond graph approach enables model-based FDI of complex mechatronics systems. In this section, bond graph based FDI methods are applied on the dynamic bond graph models of the wheels of each IAV (as given in previous chapter in Figure 4.6) for the fault identification. The structural and causal properties of bond graph are used to generate Analytical Redundancy Relations (ARRs) for the wheels of any i^{th} IAV.

ARRs are obtained directly from the bond graph model by applying a well established methodology as described in Ould-Bouamama et al. [2003]. In the latter methodology, all the sensors are dualized into signal source of effort or flow (SSe or SSf), and the considered bond graph model is assigned a preferred derivative causality. Then ARRs are derived from this bond graph model by following the causal paths from the known to unknown variables. The bond graph model of the wheel in derivative causality is given in Figure 5.3.

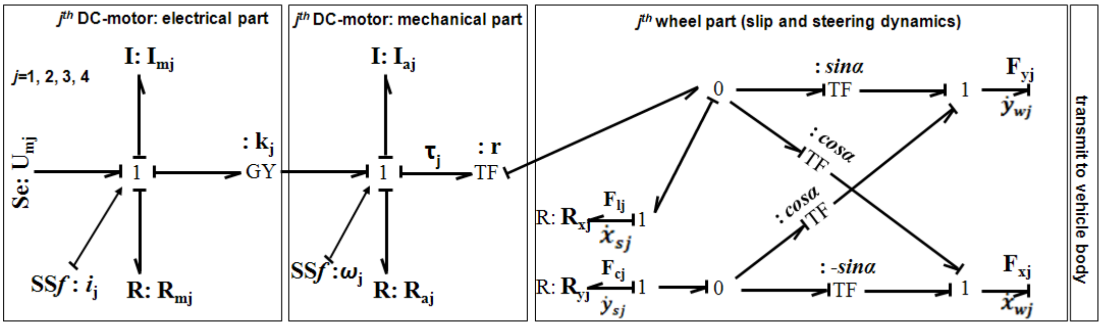


Figure 5.3: Bond graph model of a wheel in preffered derivative causality.

Refer to Figure 5.3, by applying the referred procedure two ARRs can be derived (equations 5.1 and 5.2) corresponding to the junctions where signal sources are connected.

$$ARR_{1j}^{i} : U_{mj} - R_{mj} i_j - I_{mj} \frac{di_j}{dt} - k_j \omega_j = 0 \tag{5.1}$$

$$ARR_{2j}^{i} : k_j i_j - R_{aj} \omega_j - I_{aj} \frac{d\omega_j}{dt} - \tau_j = 0 \tag{5.2}$$

ARR_{1j}^{i} and ARR_{2j}^{i} represent ARRs for j^{th} wheel of any i^{th} IAV. These ARRs are evaluated by sensors' data for FDI and if any of the two ARRs is found abnormal then there is a fault. For fault isolation, ARRs are structurally analyzed to generate a Fault Signature Matrix (FSM) as shown in Table 5.1. Basically, ARRs evaluation defines the difference between expected and observed values, which is called residual, and these residuals are used to predict faults in the system based on the predefined threshold values of the system's parameters. Faults may be detected and isolated by evaluation of FSM at any point of time. In this analysis, the sensor faults are not considered and it is assumed that there is no sensor noise.

Table 5.1: FSM for any wheel of an IAV

Components	r_{1j}^{i}	r_{2j}^{i}	M_b	I_b
U_{mj}	1	0	1	0
R_{mj}	1	0	1	0
$D_f : i_j$	1	1	1	0
I_{mj}	1	0	1	0
k_j	1	1	1	0
$D_f : \omega_j$	1	1	1	0
R_{aj}	0	1	1	0
I_{aj}	0	1	1	0
τ_j	0	1	1	0

Refer to Table 5.1, the columns represent: components of the wheel system; (r_{1j}^{i} and r_{2j}^{i} are residuals for j^{th} wheel of any i^{th} IAV); fault monitorability (M_b); and fault isolablility (I_b), respectively. If a component is presented in an ARR then '1' is assigned in the corresponding entry of FSM (means that the residual is sensitive to a fault in this component), otherwise '0' is assigned (means that the residual is not sensitive to a fault in this component). It can be noticed from Table

5.1 that none of the component has unique fault signature, thus, faults cannot be isolated but all the faults are monitorable because each fault is sensitive to at least one residual.

5.4 Reconfiguration

We propose a multilevel reconfiguration strategy for the multilevel model of ITS in Figure 5.2, which can reconfigure the SoS in case of faulty situations based on the obtained values of residuals at any instant of time. The residuals are calculated for j^{th} wheel of an i^{th} IAV in platoon. Thus, the value of a residual at any point of time informs about the health of a wheel (wheel of an IAV in platoon) to which this residual is associated.

The bond graph model-based FDI and reconfiguration methods are applied to the physical CSs, i.e., IAVs at the submicroscopic level. Consequently, the effect of faulty IAVs are observed on the micro and macro levels; moreover, reconfiguration is applied on the faulty IAVs and the effect can be realized on the higher levels. Thus, bond graph model-based FDI and reconfiguration enable whole supervision of SoS.

In Figure 5.4, the reconfiguration strategy is described for any i^{th} IAV in platoon. There are three cases for reconfiguration of the multilevel model based on the four residual groups and each group represents the two residuals r^i_{1j} and r^i_{2j} for j^{th} wheel of an i^{th} IAV in platoon.

Refer to Figure 5.4, at the submicroscopic level, faults are identified based on the four residuals groups. The proposed reconfiguration strategy recovers the SoS from faults for the cases I, II and III at the submicroscopic level. Finally, the reconfigured SoS can be realized at the microscopic and macroscopic levels. Three cases of the proposed reconfiguration strategy are as follows.

Case I: If residuals r^i_{1j} and/or r^i_{2j} are/is triggered for a fault in any one wheel of i^{th} IAV, then, the SoS can be reconfigured by making that wheel free and also making the wheel free at the opposite side of the IAV corresponding to the faulty wheel. For example, if the front left wheel is faulty then make front left and front right wheels free. It avoids over steering of the vehicle because of the angular speed difference between two opposite wheels. A wheel can be made free

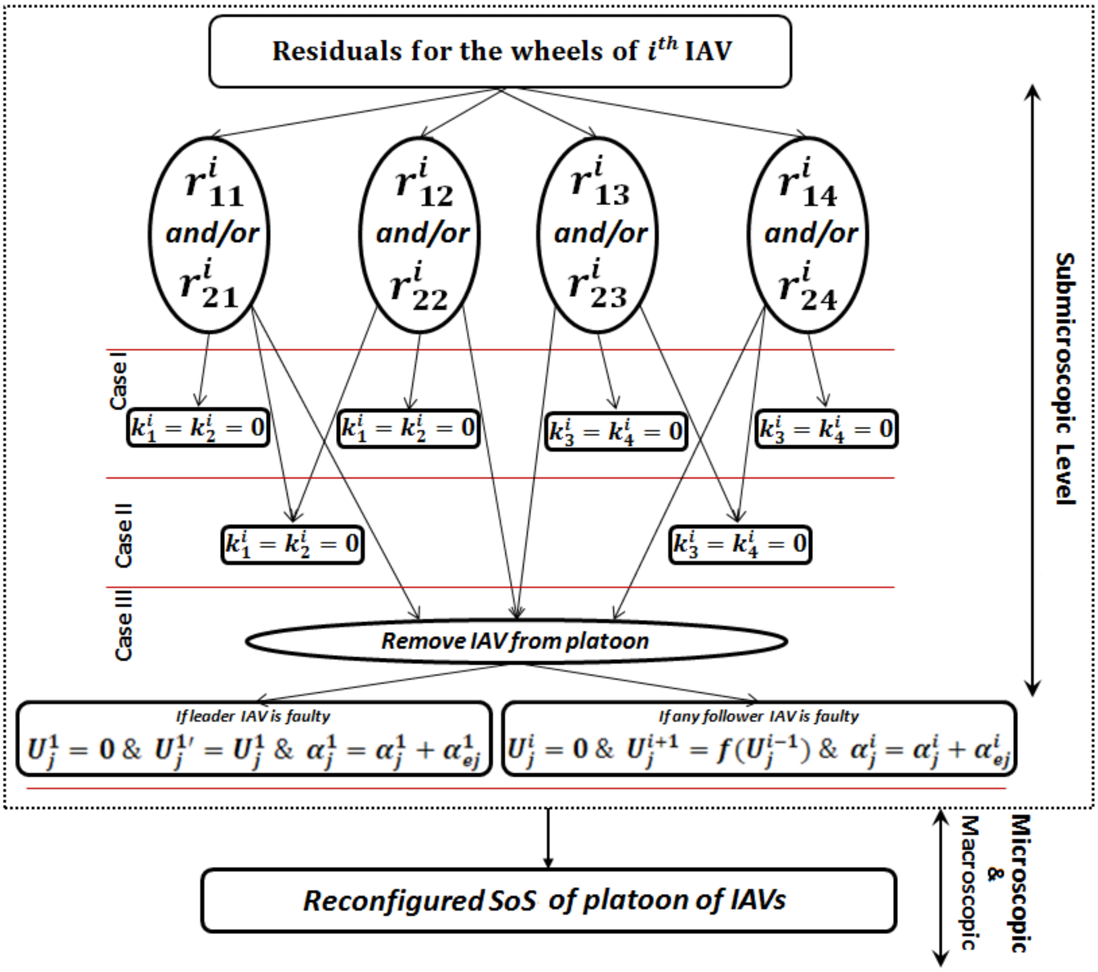


Figure 5.4: Reconfiguration strategy.

by removing the connection between the traction actuator and wheel; in that case the axle of wheel is not connected with motor, and wheel rotates freely. Mathematically, it can be achieved by assigning zero value to the torque constant k_j^i for that wheel. For example in Figure 5.5(a), the front left wheel of an IAV^i is faulty, thus, the two front wheels are made free by $k_1^i = 0$ and $k_2^i = 0$.

Case II: If two groups of residuals are faulty (only possible combinations are wheels 1,2 or wheels 3,4) then make those two wheels free by $k_1^i = k_2^i = 0$ or $k_3^i = k_4^i = 0$. For example in Figure 5.5(b), the two rear wheels of an IAV^i are faulty, thus, the two rear wheels are made free by $k_3^i = 0$ and $k_4^i = 0$.

Case III: In any other case (say more than two wheels are faulty or two faulty

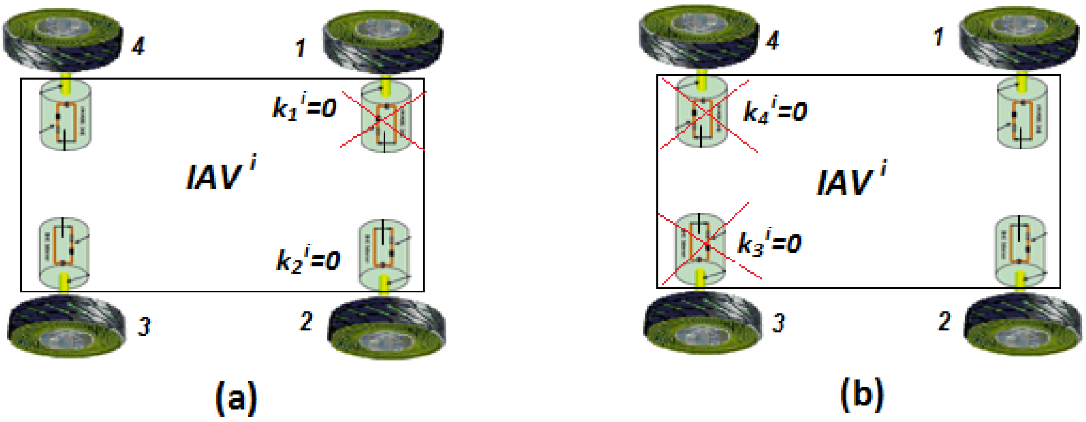


Figure 5.5: Example of the reconfiguration strategy for (a) Case I (b) Case II.

wheels are not two opposite front/rear wheels), the faulty vehicle is removed from the platoon. If the faulty vehicle is any follower i^{th} IAV, then IAV^i is removed from platoon by assigning zero value to its input voltage U_j^i and give an extra steering angle (say α_{ej}^i) to leave the platoon. Also, IAV^{i+1} following the faulty IAV^i is actuated with a voltage based on the interdistance model with IAV^{i-1}. Mathematically $U_j^{i+1} = f(U_j^{i-1})$, which means that in the recofigured system, the motion of IAV^{i+1} depends on the motion of IAV^{i-1}.

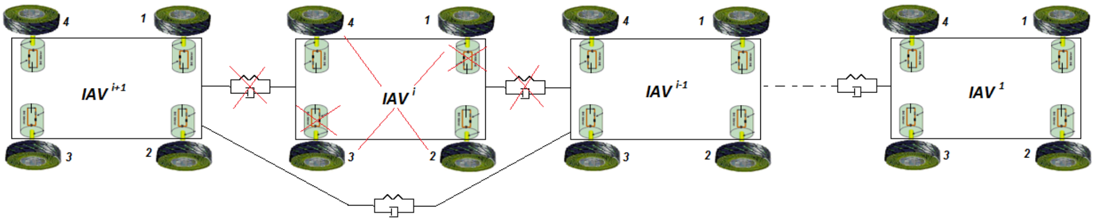


Figure 5.6: Example of the reconfiguration strategy for Case III.

If the faulty vehicle is leader IAV^1 then it is removed from the platoon in the same way ($U_j^1 = 0$ and $\alpha_j^{1'} = \alpha_j^1 + \alpha_{ej}^1$). But the follower IAV^2 becomes the leader IAV in the reconfigured system and it is actuated with an input voltage $U_j^{1'}$ equal to the voltage as given to the leader vehicle before fault. For example in Figure 5.6, the front left and the rear right wheels of an IAV^i are faulty, thus, this IAV^i is removed from the platoon by turning off its voltage supply and giving a steering angle to leave the platoon. At the same time the interdistance model is set up between IAV^{i+1} and IAV^{i-1}.

5.5 Simulation results

The developed multilevel model for supervision of a platoon of IAVs in ITS is simulated using SYMBOLS software. For simulation, we consider a platoon of four IAVs and two scenarios are simulated for the normal and faulty situations.

5.5.1 First scenario

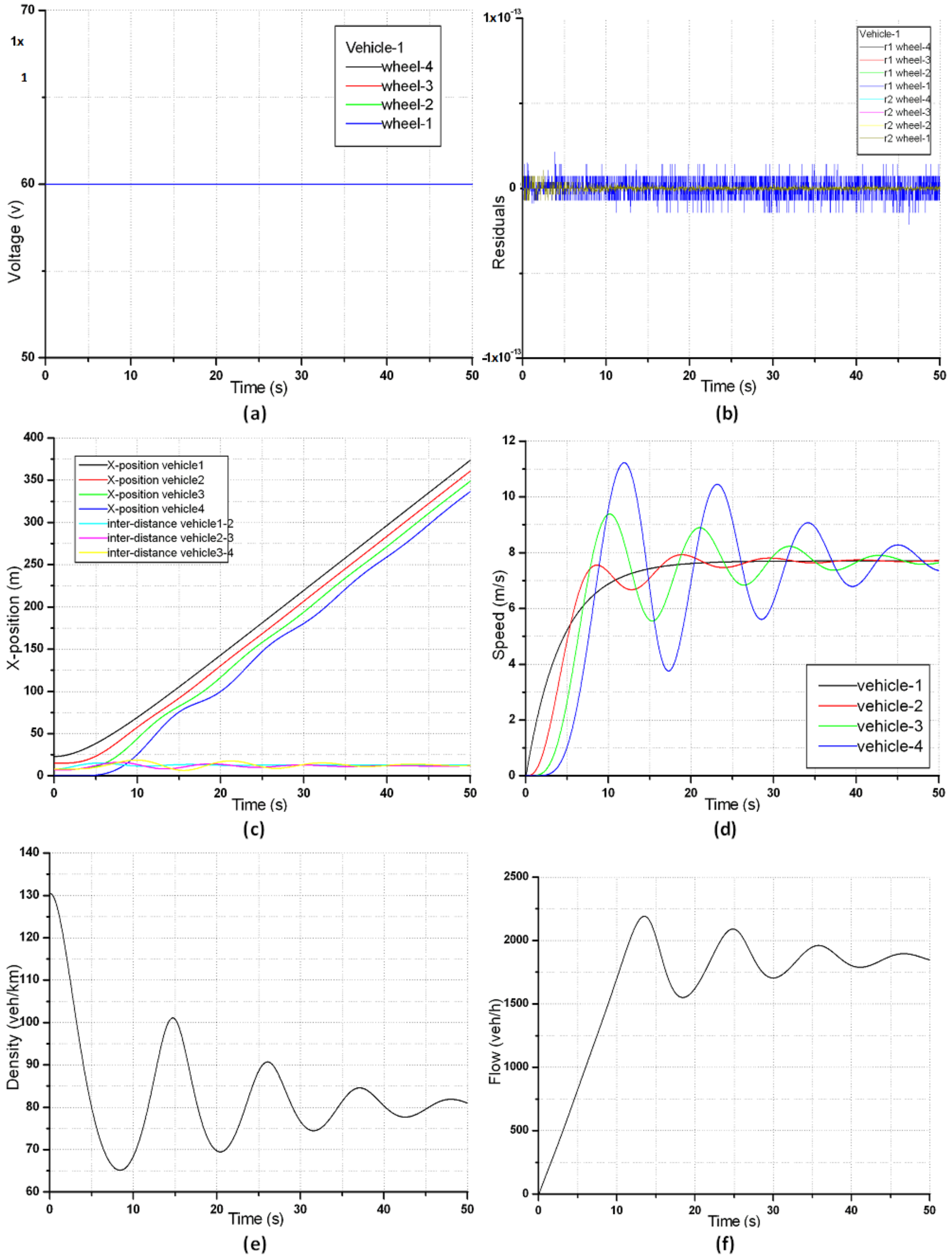
For the first scenario in simulation, a platoon of four IAVs is considered moving on a road without passing in normal situation. The simulation results are shown in Figure 5.7. At the submicroscopic level, Figure 5.7(a) and (b) show the input voltage and the values of residuals for each wheel of the leader IAV (vehicle 1) with respect to time, respectively. It can be observe that the value of each residual is zero all the time for vehicle 1, which represents the normal situation.

At the microscopic level, Figure 5.7(c) and (d) show the $x-$direction position and speed of each vehicle with respect to time, respectively. It can be observed that when a vehicle comes closer to its leader vehicle it decreases the speed and when seperation is greater it increases the speed to maintain a safe interdistance, which represents the stick-slip motion, the interdistance between each pair of vehicles is shown in Figure 5.7(c). At the macroscopic level, Figure 5.7(e) and (f) show the average values of density and flow of the traffic with respect to time, respectively.

5.5.2 Second scenario

For the second scenario in simulation, a platoon of four IAVs is considered moving on a road without passing, and a fault is introduced in the front left wheel of the leader vehicle after $10s$ by reducing its input voltage from $60v$ to $25v$ (58% reduction). The simulation results are shown in Figure 5.8. Figure 5.8(a) and (b) show the input voltage and the values of residuals for each wheel of the leader IAV (vehicle 1), respectively. It can be observed that the voltage in wheel 1 (front left) of the vehicle 1 drops to $25v$ after $10s$, and at the same time corresponding residual r_{11}^{1} is triggered to alarm about this fault.

Figure 5.8(c) and (d) show the $x-$direction position and speed of each vehicle with respect to time, respectively. It can be observed that the speed of the faulty



(a) (b)

(c) (d)

(e) (f)

Figure 5.7: First scenario in normal situation: (a) voltage in each wheel of the leader vehicle (b) residuals for each wheel of the leader vehicle (c) x-position of each vehicle and interdistance between each pair of vehicles(d) speed of each vehicle (e) density of the traffic (f) flow of the traffic with respect to time.

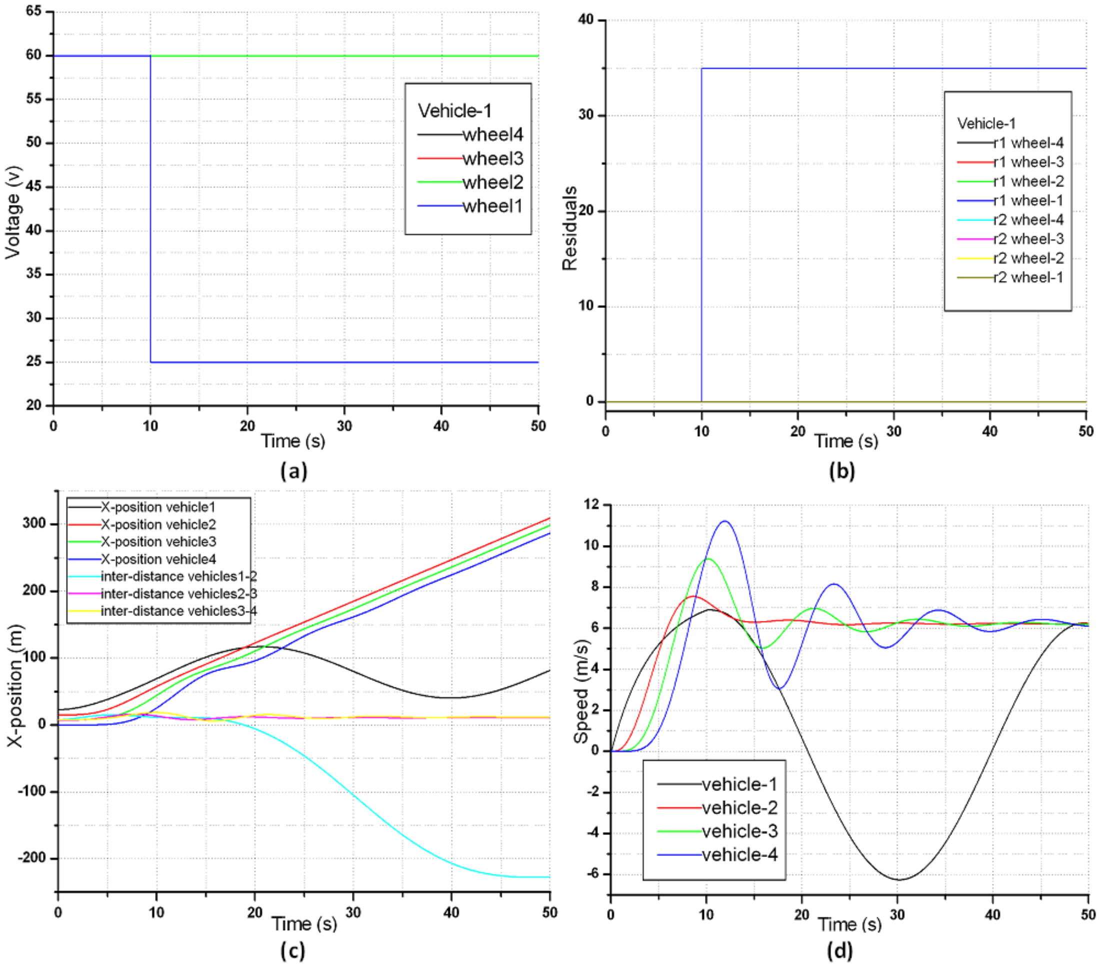


Figure 5.8: Second scenario in faulty situation: (a) voltage in each wheel of the leader vehicle (b) residuals for each wheel of the leader vehicle (c) $x-$position of each vehicle and interdistance between each pair of vehicles(d) speed of each vehicle with respect to time.

leader vehicle decreases after $10s$ and it leaves the platoon. The interdistance between vehicle 1 and vehicle 2 becomes negative, because after occurring of the fault vehicle 1 moves in a curved path (refer to Figure 5.9(b)) due to the difference between the input voltages of the two front wheels.

Thus, this faulty situation leads to failure of the global mission of SoS and it becomes important to reconfigure the SoS. Hence, the proposed reconfiguration strategy is applied to the model. The simulation results for the reconfigured model are shown in Figure 5.9. Figure 5.9(a), (b) and (c) show the trajectory of

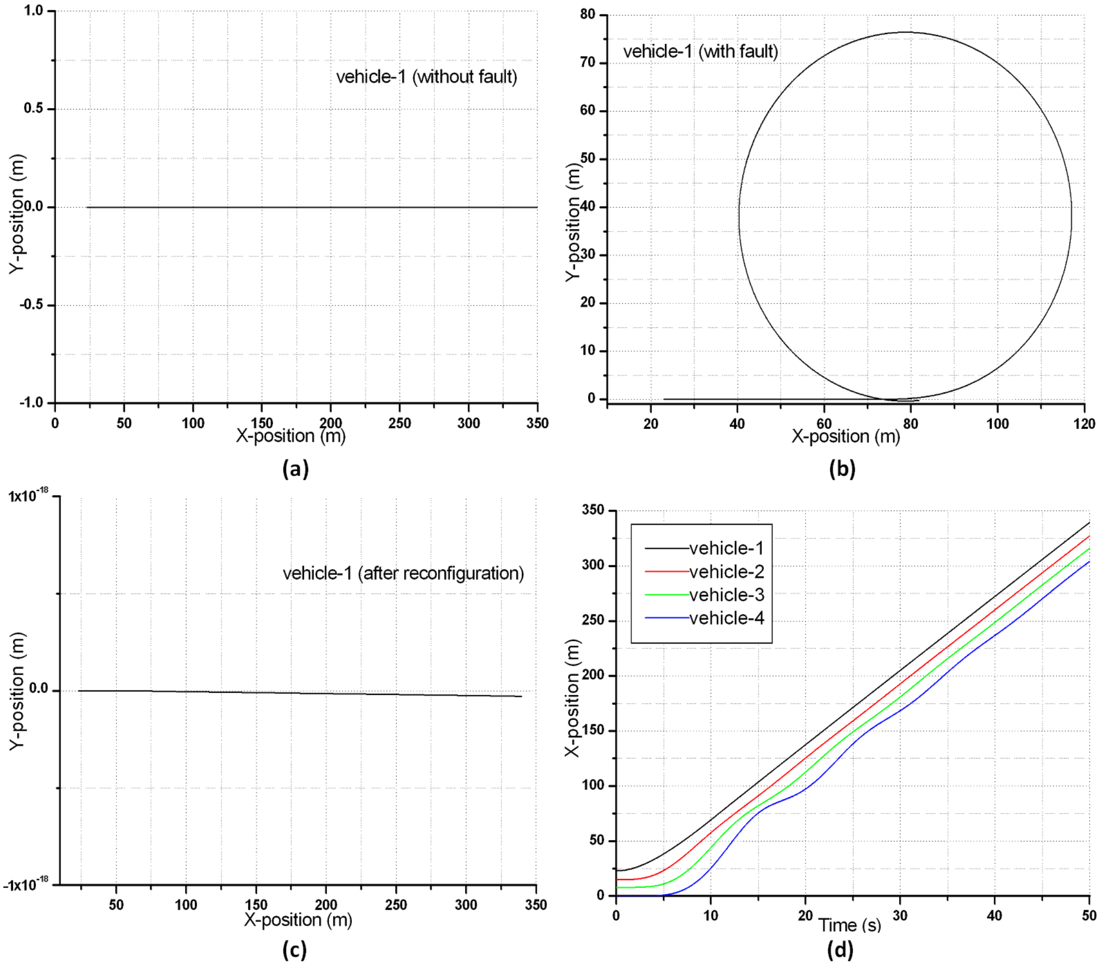


Figure 5.9: Reconfiguration: (a) trajectory of the leader vehicle in normal situation (b) trajectory of the leader vehicle in faulty situation (c) trajectory of the leader vehicle after reconfiguration (d) $x-$position of each vehicle after reconfiguration.

the leader vehicle in the normal, faulty and reconfigured situations, respectively. It can be observed that in the faulty situation the leader vehicle moves in a curved path and leaves the platoon, but after applying the reconfiguration strategy (Case I in Figure 5.4) it moves in the normal path.

In Figure 5.9(d), the $x-$position of each vehicle is shown for the reconfigured system. From these results it can be concluded that after applying the proposed reconfiguration strategy to the model, it continues to fulfill the global mission of the considered SoS in faulty situation but with a low performance, because the final position of vehicle 1 is $375m$ in the normal situation (Figure 5.7(c)), and it is $339m$ in the reconfigured model (Figure 5.9(d)).

5.6 Summary of the chapter

The multilevel bond graph model of the traffic SoS is used for supervision of a platoon of IAVs in ITS. The structural and causal properties of bond graph are used for fault detection and isolation, which enables to detect the faults at the lower level (physical CSs) and to evaluate their effects at the higher levels. Finally, the multilevel model-based reconfiguration strategy is proposed to recover the platoon from the faulty situations, and to continue to achieve its global mission. After analysing the simulation results for a platoon of four IAVs, it can be concluded that the multilevel model performs well in the normal situation as well as in the faulty situation after applying the proposed model-based reconfiguration strategy but with degraded performance in case of faults. In this way, the whole supervision of SoS can be performed using the proposed multilevel bond graph model.

Conclusion

A SoS is a large-scale integrated system, and composed of independent heterogeneous systems which are complex themselves. In addition, a SoS exhibits specific properties (operational and managerial independence, geographical dispersion, emergent behavior, and evolutionary development) which differentiate it from the traditional complex systems. Theory and principles of SoS have not been well established yet. Thus, modeling of SoS is challenging but very important for control and supervision purposes. It is found that most of the contributions in the area of SoS modeling are based on the organizational modeling approach. The organizational model of a SoS cannot describe the dynamics of the physical CSs within it. Thus, it is difficult to analyze the dynamic behavior of the physical CSs if there are some perturbations. For example, if status of a physical CS (level-0) is faulty, then, this fault can propagate to the higher levels (level$\neq$0), and finally results in failure of the global mission of a SoS. In this case, it is important to know the origin of the fault at the level-0 in order to anticipate on the evolution of the whole SoS.

In the present work, a method for the organizational and behavioral modeling of a class of SoS (engineering mechatronic systems) is proposed based on the bond graph modeling approach. This is achieved by the dynamic modeling (behavioral modeling) of the physical CSs of a SoS; and then extending this behavioral modeling to the organizational modeling of the considered SoS using the same bond graph approach. A SoS is organized into various levels based on its complexity. In a SoS, CSs at the lowest level (level-0) represent the physical CS, while CSs at the higher levels (level$\neq$0) are the non-physical CSs, which are formed by the organizations of CSs at the levels lower than their own levels. Moreover, the fundamental properties of a SoS include: operational independence, managerial independence, geographical dispersion, emergent behavior, and evolutionary development. These properties are mathematically described based on the bond graph approach.

The procedure for the bond graph modeling is exemplified by modeling a mobile robot called 'Robotino'. A group of Robotino working collectively for a common mission can be considered as a SoS, because each Robotino is operationally and managerially independent, and can achieve its own mission independently. The bond graph model of Robotino is developed, and the structural and behavioral analysis is performed on the model to generate its dynamic equations, and to apply FDI methods. The higher level non-physical CSs are modeled based on information exchange to represent their organization in SoS. Finally, a multilevel model of a SoS is obtained by combining all the levels, thus, this model includes the behavioral models of the physical CSs and the organizational model of the SoS using a single modeling tool i.e., Bond graph. The proposed multilevel bond graph model can be used for supervision of the whole SoS.

The proposed approach for SoS modeling is applied to an ITS (*ITS is a broad term and it is applicable to all modes of transport, in the present work, we consider only the road traffic dynamic in a platoon of IAVs*). The traffic dynamic in a platoon of IAVs can be modeled at various levels of a SoS. The IAVs represent the physical CSs of the considered traffic SoS, because they are operationally and managerially independent. Furthermore, they are geographically dispersed, with a continuous exchange of information (V2V communication) among them. The organization of IAVs represents the CSs at the higher levels; finally they can structurally make a self-reconfiguration of their organization to achieve the global mission of the SoS.

In literature, the traffic dynamic is described by four abstraction levels namely, submicroscopic, microscopic, mesoscopic, and macroscopic level. We develop a multilevel model of the traffic dynamic as a SoS, considering three levels namely submicroscopic, microscopic, and macroscopic level. The mesoscopic level modeling is not considered in this work. At the submicroscopic level, we develop the bond graph model of an IAV considering the longitudinal, lateral, yaw, and actuator dynamics. At the microscopic level, a car-following model is developed based on virtual interconnections model between the submicroscopic bond graph models of IAVs, which represents V2V communication. Then, at the macroscopic level, macroscopic variables (average speed, density, and flow) are deduced from the submicroscopic and microscopic models. Finally, all the levels are combined to develop a multilevel model of the traffic dynamic using a single modeling approach called bond graph.

The bond graph model can be used to derive the dynamic equations of the system using its causal and structural properties. The multilevel model enables to analyze the effects of the faulty IAVs on the various levels of the traffic SoS. The model is simulated for the normal and faulty situations in a platoon of IAVs. From the simulation results in normal situation, it is observed that the interdistance model between the leader and the follower vehicles shows an stick-slip motion, in which, when the follower vehicle comes closer to the leader vehicle it applies brake, and again accelerates when the separation is greater in order to maintain a safer interdistance with its leader vehicle. From the simulation results in faulty situation at the submicroscopic level, the effect of a faulty vehicle can be observed at the microscopic and the macroscopic levels. Finally, the multilevel model of traffic is validated on a real-time simulator of vehicle dynamics. In addition, real experiments on IAVs are performed to validate the model.

The proposed multilevel model of the traffic SoS is used for supervision by applying bond graph based FDI methods on IAVs, considering faults on the wheels. Then, a multilevel reconfiguration strategy is proposed to recover SoS from faulty to normal situation. The proposed reconfiguration strategy is a model-based reconfiguration approach for the physical CSs. The model is simulated considering fault on a wheel of an IAV in the SoS. The effect of this fault propagates from the submicroscopic level to the higher levels, which leads to failure of the mission of the SoS. But, after applying the proposed reconfiguration strategy the faulty vehicle recovers to a healthy situation, and continue to contribute in the SoS. It is noticed that after applying reconfiguration strategy, the SoS is able to achieve its global mission in normal as well as in faulty situation, but, with a low performance in case of faulty situation.

Future work

The main limitations of the proposed model are the following, which are interesting to be addressed in future work.

- In the present work, communication between vehicles is modeled using information bonds in bond graph, assuming that there is no communication delay. But, communication delay is a critical issue, and it is important to model this delay for ensuring more safety in a platoon of vehicles. Thus, it is interesting to model communication delay using bond graph, in future work.
- The main contribution of the present work is **modeling** of a SoS, and the proposed model can be used for supervision purpose using causal and structural properties of bond graph, which is explained in Chapter 5. The limitation is that the bond graph-based structural analysis is applied only on the physical CSs for supervision and control; while it is still an open question that how we can extend the bond graph-based structural analysis to the highere level organizational CSs. Thus, it is an interesting future work to extend the bond graph-based structural analysis to the organizational CSs for the purpose of control and supervision in a SoS.

In addition, the following points can be considered for future work:

- In the present work, we considered a class of SoS, i.e. engineering mechatronic systems; but it is interesting to extend the approach for modeling other classes of SoS such as biology, healthcare, economics, etc. For example, it is interesting to model the behavior of animals in a group as SoS.
- The proposed multilevel bond graph model of a SoS can be used for applications in other large-scale mechatronic systems such as, space exploration SoS, swarm robotics SoS, etc.
- The proposed multilevel model of the traffic SoS can be used in future for calculating the energy consumption for different scenarios in the traffic dynamic, because bond graph is a energy based modeling approach.

- It is interesting to add more dynamics of IAVs such as, pitch and roll dynamics. Furthermore, lane-changing scenario and phenomena of signal switching at the crossing can be modeled in the traffic flow, and to analyze their effects on the higher levels of the SoS. Finally, different reconfiguration strategies can be developed based on the considered dynamics of a physical CS, which results in the whole supervision of the considered SoS.

Appendix I

Abstract of the deliverable 1

Existing ICT Tools Guide on Private Logistics Organization: State of the Art- Recent years have witnessed a growing awareness of the extent to which ICT permeates all our society and economy. In the last two decades we have seen a revolutionary change in society, just because of ICT. Now, we can see the applications of ICT in various fields viz. education, health, public transport, freight transport, infrastructure, business, office and even at home.

In this study, we focus on the application of ICT in freight transport, and in particular the impact of ICT on greener freight transport. The past decade (the 1990s) saw a rigorous development in ICT with the advent of wireless networking and mobile communication. Now, it is usual to locate the position of a moving vehicle with the help of tracking and tracing devices. Smart cards, e-business portals, intelligent vehicles, real time monitoring and control, safety and security systems are few innovations that ICT is bringing to transportation.

This study reports about the current and future scenario of information and communication technology in freight transport. Many researchers have been contributed to integrate the transport and ICT, which results to introduce an intelligent transport system (ITS). The points covered in this study are as follow: (i) a literature review of the role of ICT in freight transport, (ii) an identification of the different components of freight transport system, (iii) a description of the applications of ICT for these components of freight transport system, (iv) an identification of ICT tools available for these applications, and (v) the advantages and limitations of using ICT in freight transport.

APPENDIX I

Abstract of the deliverable 2

Existing ICT Tools Report for Public Sustainable Infrastructure Planning and Management- ICT enables for achieving the goal of long term sustainable freight transport. For the optimum utilization of the transport infrastructure, it is required to implement recent ICT tools and technologies.

This report describes state of the art ICTs for the public sustainable infrastructure. The report considers the technologies for the transport infrastructures namely road, rail, water and container terminals. Various existing technologies are described for different applications in freight transport infrastructure.

Abstract of the deliverable 3

ICT Requirements Synthesis- The freight transport is an important sector for economy of any country and in Europe freight transport is rapidly growing with time. In this way, the sustainability of freight transport system becomes important, and many challenges for sustainable transport like pollution, congestion, safety, etc. are required to be solved. It is identified that integration of ICT in logistics can help in achieving the goal of sustainable freight transport.

The present report describes the freight transport activities for different transport modes viz. road, rail, water, and intermodal. The report provides a synthesis on ICT use in logistics sector in Europe. The synthesis is based on the reports from different European projects and many research papers. The major challenges for sustainable freight transport are identified in the report and many ICT based solutions are suggested. Moreover, some gaps based on ICT requirements in logistics are mentioned in the report, and finally an ICT based recommendation is proposed for the road traffic management as road transport is the most used mean of freight transport and causes most of the emissions generated by the freight transport system.

Abstract of the deliverable 4

Knowledge Database on ICT and Telematics Tools- This deliverable is a database of existing ICT tools like Radio Frequency Identification (RFID), Global Positioning System (GPS), Geographic Information System (GlS), Optical Character

Recognition (OCR), Electronic data Interchange (EDI), WiFi, WiMax, Cellular Networks (GSM/ GPRS/ EDGE/ UMTS), Automatic Identification Services (AIS), etc. The database provides technical specifications for various ICT tools with their potential applications (tracking and tracing, communication, monitoring and control, etc.) in different transport modes viz. road, rail, and water. In addition, applications of ICT are identified in port terminal activities and miscellaneous applications like business functions, automatic toll collection, etc.

APPENDIX I

Appendix II

A.1 Bond graph modeling

The bond graph modeling approach was invented by H. M. Paynter in 1959 (Paynter [1961]). Bond graph is a unified graphical approach for modeling systems of different domain like mechanical, thermal, electrical, etc. This approach is based on the power exchange phenomena between elements of a system. The key feature of the bond graph modeling is the representation of exchange power (by a bond with half-headed arrow) as the product of generalized efforts (e) and generalized flows (f) with elements acting between these variables and junction structures (algebraic constraints) to reproduce the global model as interconnected subsystems. These generalized effort and flow variables are described for various physical domains in Table 5.2.

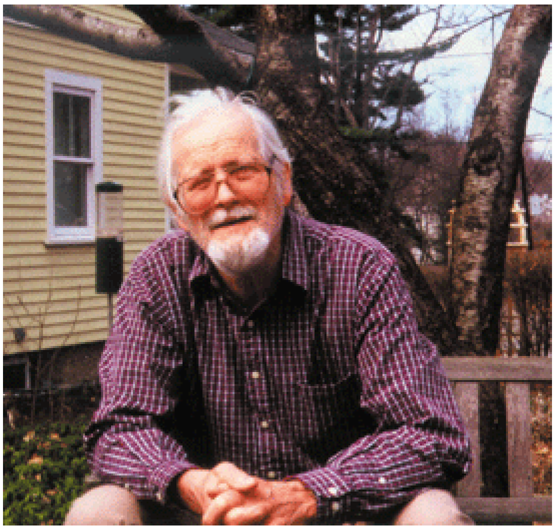


Figure 5.10: Professor Henry M. Paynter (1923-2002)

Bond graphs are labeled as directed graphs, in which the vertices represent sub-models (or elements) and the edges represent an ideal energy connection between elements. Any physical system can be modeled with the following generalized bond graph elements (Table 5.3):

- Active elements which provide input power to the system (source of effort Se and source of flow Sf).

Table 5.2: Effort and flow variables in different physical domains.

Physical domain	effort (e)	flow(f)
Mechanical (Translational)	Force (F)	Velocity (v)
Mechanical (Rotational)	Torque (T)	Angular velocity (ω)
Electrical	Voltage (V)	Current (i)
Hydraulic	Pressure (P)	Volume flow rate (Q)
Thermal	Temperature (T)	Entropy flow rate ($\dot{s}$)

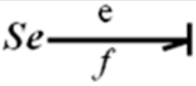
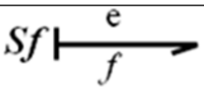
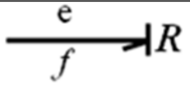
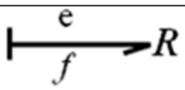
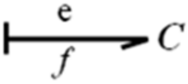
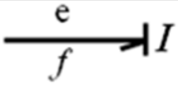
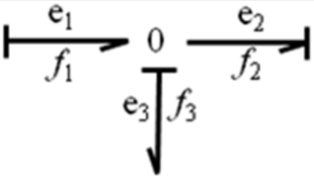
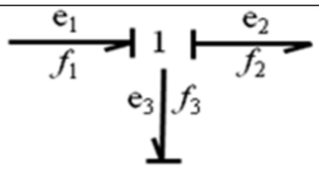
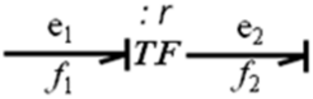
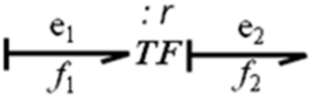
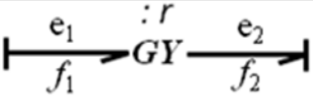
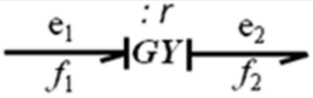
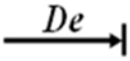
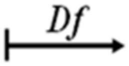
- Passive elements transform input power into dissipated energy (resistance R) and stored energy (capacitance C and inductance I).
- Power conserving elements (common effort junction 0, common flow junction 1, transformer *TF*, and gyrator GY).

Besides these elements, the various outputs of a system are measured using sensors which are represented by the full-headed arrows in bond graph. These full-headed arrows are flow/effort activated bonds (not power bonds). The activated bonds are used only for measurements (detector of effort *De* and detector of flow *Df*) and do not contribute to any power flow. The values of some bond graph elements may depend on the system states and other variables of a system, in this case, the elements are called modulated elements, for example modulated source of effort *MSe*, modulated transformer *MTF*, etc. In this way, bond graph enables to develop the dynamic model of any system using bond graph elements and power exchange among these elements, while information exchange can be modeled using activated bonds. The description of bond graph elements in integral causality is given in Table 5.3 with their constitutive relations.

A.2 Causality

An important property of the bond graph is the causality. The latter enables to define the cause-effect relations in a system. Causal analysis determines the direction of effort and flow information exchange in a bond graph. The type of causality used in a model is related to the causality assigned to the storage elements I and C. Indeed, the causality assigned to these elements determine if either an integration or a differentiation with respect to time is required. For the

Table 5.3: Description of the bond graph elements.

BG element	Element with integral causality	Constitutive relation
Se (source of effort)		$Se = e$
Sf (source of flow)		$Sf = f$
R (resistance)		$f = \frac{1}{R}\, e$
		$e = R\, f$
C (capacitance)		$e = \frac{1}{C}\int f\, dt$
I (inductance)		$f = \frac{1}{I}\int e\, dt$
$0 - junction$ (common effort junction)		$e_1 = e_2 = e_3$ $f_1 = f_2 + f_3$
$1 - junction$ (common flow junction)		$f_1 = f_2 = f_3$ $e_1 = e_2 + e_3$
TF (transformer)		$e_2 = r\, e_1\,;\quad f_1 = r\, f_2$
		$f_2 = r\, f_1\,;\quad e_1 = r\, e_2$
GY (gyrator)		$e_2 = r\, f_1\,;\quad e_1 = r\, f_2$
		$f_2 = r\, e_1\,;\quad f_1 = r\, e_2$
De (effort measurement)		$De = e$
Df (flow measurement)		$Df = f$

storage elements the causal strokes in preferred integral causality are assigned as illustrated in Figure 5.11 (a). Computationally it means that the inertia element accepts an effort as input and produces a flow as output, while the capacitor accepts flow as input and produces effort (5.3).

$$\begin{cases} f_I = \frac{1}{I}\int e_I dt, \\ e_c = \frac{1}{C}\int f_C dt \end{cases} \tag{5.3}$$

If a derivative causality is assigned, as in Figure 5.11 (b), the I elements accepts a flow as input and produces an effort as output, while the C element accepts effort as input and produces flow as output (5.4).

$$\begin{cases} e_I = I\frac{df_I}{dt}, \\ f_C = C\frac{de_C}{dt} \end{cases} \tag{5.4}$$

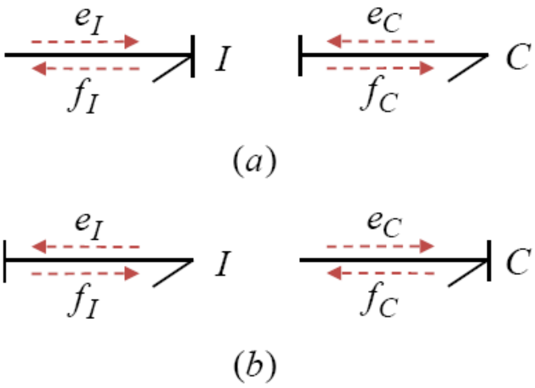


Figure 5.11: Storage elements I and C in (a) integral causality and (b) derivative causality.

Causal propagation is useful to analyze bond graph model. Indeed the causal strokes give information about causal conflict (incompatibility of equations), derivative causalities (loss of states), algebraic and causal loops (solvability and complication level of the numerical model), and control and monitoring properties.

A.3 State-space equations from bond graph

The system state-space equations can be derived from a bond graph model by introducing the constitutive equations for each subsystem (behavioral equations) and the constraints imposed by the junctions (conservation law equations). The dimension of the state vector is equal to the number of I and C elements in integral causality. Moreover, the state vector of a system (x) is composed of energy variables p and q associated to the I and C elements, respectively.

$$x = \begin{bmatrix} p_I \\ q_c \end{bmatrix} = \begin{bmatrix} \int e_I \\ \int f_C \end{bmatrix} \tag{5.5}$$

The state variables are not presented in a bond graph model, only their derivative.

$$\dot{x} = \begin{bmatrix} \dot{p}_I \\ \dot{q}_c \end{bmatrix} = \begin{bmatrix} e_I \\ f_C \end{bmatrix} \tag{5.6}$$

In general, for a bond graph model with no derivative, causalities, the state-space equations can be deduced through following steps:

1. Write constitutive equations of each element (*R, C, I*),

2. write structural or constraint laws associated with junction structure (0, 1, *TF, GY*),

3. and finally combine these different laws to obtain equation through sequential ordering and substitutions.

A.4 Structural analysis

In the context of modeling, control synthesis and fault diagnosis, most results are usually dependent on the systems parameters. This fact prevents from obtaining valid information about the system at an early design stage. In addition, once a parameter is modified, a new analysis phase must be conducted in order to verify if the results on systems performance remain valid. This is where the role of structural analysis is introduced. Indeed, structural analysis enables results to be obtained by analyzing the structure of the system information, and therefore being valid for most values of numerical parameters. Among the graphical representations in which structural analysis can be performed, one can refer to the bipartite graphs (Blanke et al. [2003]), bond graphs (Samantaray and Bouamama [2008]), and linear graphs (Boukhobza et al. [2007]).

A bond graph model allows to perform structural analysis, and enables to deduce a variety of structural properties, such as: system controllability, observability, diagnosability, etc. This analysis only depends on the types of elements (bond graph) composing the system, and on the way that they connect between each other regardless of their numerical value.

Structural controllability and observability can be directly concluded from a bond graph model without the use of any calculations, as proposed in (Sueur and Dauphin-Tanguy [1991]).

Definition A.1: The system is structurally controllable if and only if two conditions are satisfied:

- There is a causal path connecting a source to each *I*, and *C* element in integral causality;
- All *I* and *C* elements accept a derivative causality. If this is not completely respected, a dualization of the sources is required to put all *I* and *C* elements in derivative causality.

Definition A.2: The system is structurally observable if and only if two conditions are satisfied:

- There is a causal path connecting a detector to each *I*, and *C* element in integral causality;
- All *I*, and *C* elements accept a derivative causality. If this is not completely respected, a dualization of the detectors is required to put all *I*, and *C* elements in derivative causality.

Moreover, causal and structural analysis of a bond graph model enables to perform FDI and FTC on a system, which leads to the whole supervision of the system. The more details on the bond graph based modeling, control, and supervision can be referred to the following references: Dauphin-Tanguy et al. [1999]; Ould-Bouamama et al. [2003]; Samantaray and Bouamama [2008]; Borutzky [2009]; and Merzouki et al. [2012].

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