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Perspective

Linear-graph Modeling of a Social System Using Multi-agent Mechatronics

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Abstract: The present paper concerns linear graphs, multi-agent systems, Mechatronics, and social systems. Specifically, the paper focuses on developing a linear graph-based multi-agent, mechatronic model for a social system. Even though linear graphs have been used in the analytical modeling of engineering systems, their use in modeling social systems is found to be innovative. Generally, a linear-graph model may be used for many purposes including computer simulation, system design, optimization, control, and malfunction diagnosis and repair. The paper will first discuss the relevance of multi-agent systems and mechatronic concepts in the present goal connected to social systems. In particular, it indicates the analogy of mechatronic concepts and the concepts of equity, diversity, and inclusion (EDI) of a social system. This analogy relates EDI to optimal or unique outcome, unified methodology, and integrated treatment in a general mechatronic system. Linear graphs (LGs) use lines to represent system elements, and the interconnection of these lines (branches) will generate the system model, in a graphic form. In this manner, an LG will provide a graphical representation of the true physical structure of the modeled system, allowing visualization of the system structure. Furthermore, LGs facilitate an integrated treatment, where all physical domains are represented in a single LG. Besides, LGs facilitate a unified treatment, where analogous methodology is used for different physical domains, which is a significant advantage in model development. In this manner, through the present analogy, the present paper indicates how a linear-graph model can be developed for a social system.

Keywords: mechatronic systems; linear graphs; analytical modeling; social systems; multi-agent systems.

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1 Introduction

Multi-agent systems, Mechatronics, and linear graphs form the technical basis of the present paper[1, 2]. These methodologies, through appropriate analogies, are used to propose a modeling approach for a social system. The concept of relating mechatronic systems and linear graphs to social systems, is entirely new. Hence a state-of-the-art is not available for this concept. However, analytical modeling of engineering systems, some using linear graphs, is a well-established area. Furthermore, some work has been done on dynamic modeling of social systems, mainly by Forrester[3-5]. Hence the presented state-of-the-art mainly concerns analytical modeling in general. The mechatronic linear graph model explored in the present work concerns a social system that encompasses equity, diversity, and inclusion. In the foregoing sections, first technical foundation of the basis of model development is presented. Next, the concepts of a social system encompassing equity, diversity, and inclusion is described. As needed, the analogies between multi-agent mechatronics and EDI are indicated. Then the proposed linear-graph modeling of a social system is described, along with an example of linear-graph model of a community unit.

2 Multi-agent systems

Many techniques of modeling are available[6-13]. The technique of modeling that is explored in the present work uses a linear-graph method, which is centered on multi-agent Mechatronics. In a multi-agent system (MAS) [14-18], the agents work together to carry out the needed actions or make decisions regarding the needed actions. In an engineering system, the agents may be robots, machines, sensors, actuators, controllers, and other devices. In a social system, as needed, agents are mainly humans. Some such systems may contain machines (like robots) that the humans interact with or use. The operation of an MAS will be facilitated through cooperation of agents, as a network. Some of the networked agents (e. g., robots, unmanned aerial vehicles or UAVs, and sensor nodes) and their environment can be dynamic (mobile). Hence, the model itself should take mobility into consideration, and implement effective and adaptive control strategies to accommodate the required situations.

In a man-machine system, agents would be humans and machines like robots, both. As noted, in a social system, the agents are typically community members, and machines that they interact with. The structure of a multi-agent system is shown in Figure 1, as originally proposed in[15]. The structure of the decision making module, which consists of a Knowledge Base, Data Base, and Inference Engine, has been fully explained in[19]. Reconciliation, as indicated in Figure 1, is strictly an activity of fusion of inferences that come from the system agents.

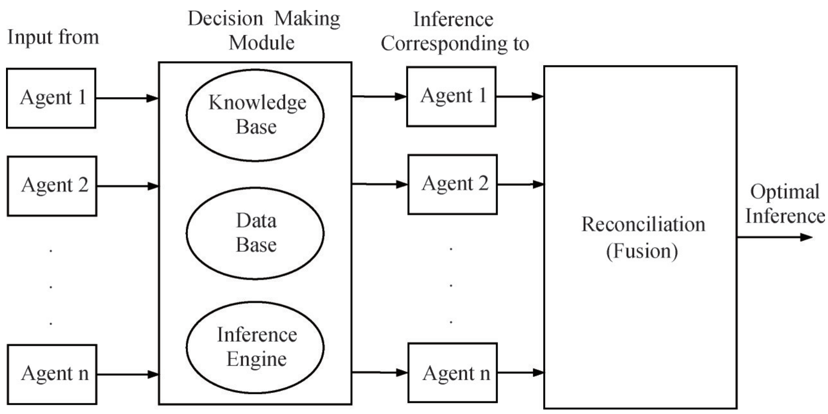

Fig.1 The structure of a multi-agent system.

The system architecture may be either hierarchical (centralized) or decentralized (distributed], as shown in Figures 2 and 3, respectively. These structures were originally proposed in[15]. In a hierarchical or centralized structure (Figure 2), the top level decision-maker determines the required cooperative tasks and assigns them to the immediately lower level agents, and so on. Upper level decisions are communicated down the chain of command. Agents determine the most appropriate actions for themselves, and make appropriate decisions. The concept of self-awareness, as in systems of artificial intelligence, is applicable here.

In a decentralized or distributed structure (Figure 3), the agents have equal power to make decisions. If a group leader is not assigned in such a system, a leader may be chosen, if required, in consensus of all members in the group. Such an assignment is typically temporary. Furthermore, the leader does not have autocratic power, unlike in a centralized system.

3 Use of Mechatronics

The term Mechatronics originated by combining the two terms "MECHAnics and elecTRONICS," in 1969, by Yasakawa Electric Co. in Japan. In the beginning they had the copyright for the term. But now it is released for public use. The original definition of the field of Mechatronics commonly specifies the synergistic application of mechanics, electronics, control engineering, and computer science in the development of electromechanical products and systems, through integrated design. There is some validity in this conventional definition. Key aspects of that definition are "synergistic" application, multiple domains (mechanics, electronics, control engineering, computer science), "electromechanical" products and systems, and "integrated" design. Here "synergistic" means combining two aspects would lead to a level of performance that would be better than the sum of their individual performances. In lay terms this implies 1+1 > 2. Integrated design means, different components of the system will be designed by considering them together, not separately. Also, it should be noted that the original definition is limited to "electromechanical" products.

An enhanced definition of a mechatronic system has been established[1]. It incorporates the terms "integrated design" and "unified methodology," which generates an "optimal" or "unique" solution, by following a

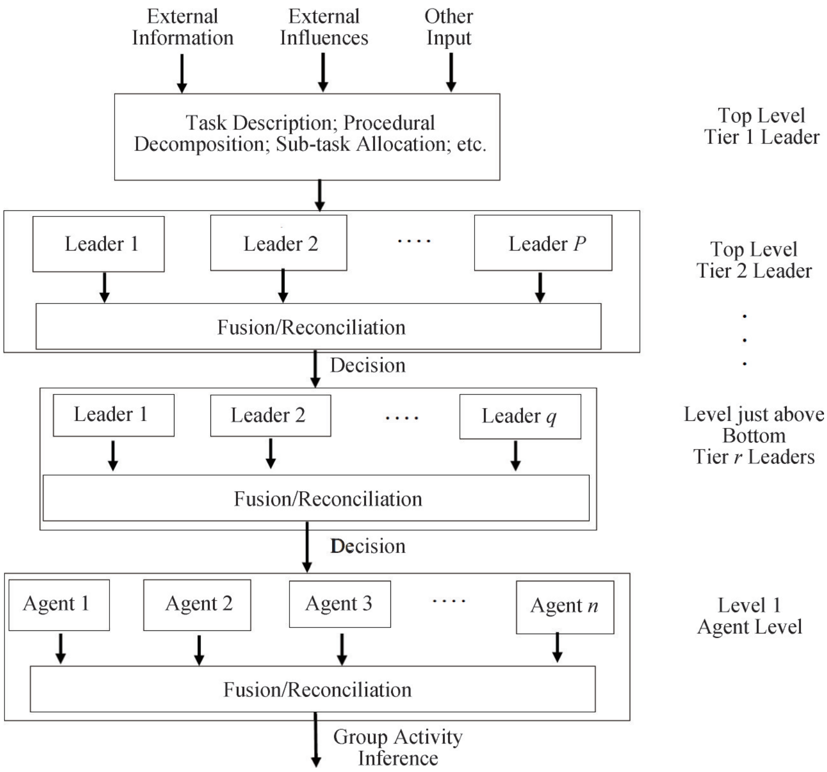

Fig.2 A hierarchical or centralized structure of organization.

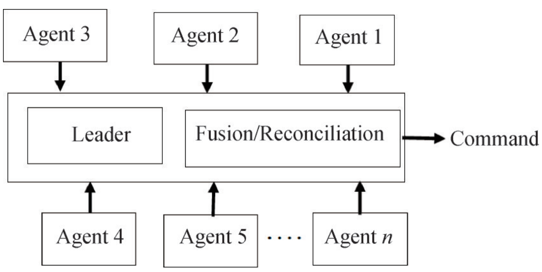

Fig.3 A decentralized or distributed structure of organization.

"systematic procedure." As in the original definition of Mechatronics "integrated" means, a concurrent or simultaneous treatment of the system design, where all physical domains of the system are considered simultaneously. This treatment should consider "dynamic coupling" or "dynamic interactions" or "energy conversion" that exist among the system components. Most important, added aspect in the enhanced definition is the use of unified methodology. This means, the system analysis would employ analogies or similar approaches for all physical domains in the system. In view of this important aspect, the approach of linear graphs is quite suitable for the associated system modeling[1,2]. The main focus of the present paper is the use of linear graphs for modeling a social system consisting of different types of agents, mainly humans. Also important in the extended definition of Mechatronics is its applicability to multi-physics systems including other domains such as fluids and thermal systems, not just electromechanical systems. The present paper further extends the definition of Mechatronics to non-physics systems, particularly social systems. In this backdrop, in the present paper, Mechatronics is applied to the realization of EDI within a social community.

Motivation for the developments of mechatronic products may be mentioned here. In particular, sequentially designed and instrumented components are not optimally matched. Concurrent (integrated) and optimal design and instrumentation will imply optimization of the final outcome. In a sequential design, even if the individual subsystems are optimal, the interconnected overall system will not be optimal. It follows that, an integrated mechatronic design will lead to improved performance. Some other benefits exist as well, for example, increased efficiency, cost effectiveness, ease of system integration and expansion or enhancement, compatibility and ease of cooperation with other systems, improved controllability, increased reliability, and increased product life. Each of these claims may be confirmed through the definition of a mechatronic system.

3.1 Mechatronic Model Development

The development of a lumped-parameter analytical model for an engineering mechatronic system that involves mechanical, electrical, fluid, and thermal domains, consists of the following steps: Write lumped element equations, also known as constitutive or physical equations, for physical components (mechanical, electrical, fluid, and thermal), simplify these equations using inter-domain analogies (for a unified treatment), along with compatibility relations for across-variables and continuity relations for through-variables. Here, an across-variable varies across the considered element (E. g., velocity, voltage, temperature), and a through-variable remains unchanged through the considered element (E.g., force, current, fluid flow rate, heat transfer rate). These are summarized in Table 1.

Two types of energy-storage elements are involved, which define the state variables of the system[1]. They are A-type elements, where the state variable that represents the dynamics of the element is an across-variable, and T-type elements, where the state variable that represents the dynamics of the element is a through-variable. The energy dissipating elements are termed D-type elements, and they do not define state variables. The associated constitutive equations for linear lumped-parameter elements in four physical domains are given in Table 2.

Table 1 Through- and across-variable pairs in several physical domains.

System Type (Domain)	**Through-variable**	**Across-variable**
Electrical	Current	Voltage
Fluid	Flow Rate	Pressure
Mechanical	Force/Torque	Linear Velocity/ Angular Velocity
Thermal	Heat Transfer Rate	Temperature

Table 2 Linear constitutive relations for several physical domains.

System Type	Constitutive Relations for		
	Energy Storage Elements		Energy Dissipating Element
	A-Type (Across) Element	*T*-Type (Through) Element	*D*-Type (Dissipative) Element
Mechanical (Translatory): v = velocity f = force	Mass $m\frac{dv}{dt}=f$ (Newton's 2nd Law) m = mass	Spring $\frac{1}{k}\frac{df}{dt}=v$ (Hooke's Law) k = stiffness	Viscous Damper $v=\frac{1}{b}f$ b = damping constant
Electrical: v = voltage i = current	Capacitor $C\frac{dv}{dt}=i$ C = capacitance	Inductor $L\frac{dI}{dt}=v$ L = inductance	Resistor $v=Ri$ R = resistance
Fluid: P = pressure difference Q = volume flow rate	Fluid Capacitor $C\frac{dP}{dt}=Q$ C_f = fluid capacitance	Fluid Inertor (Inductor) $I_f\frac{dQ}{dt}=P$ I_f = inertance	Fluid Resistor $P=R_fQ$ R_f = fluid resistance
Thermal: T = temperature difference Q = heat transfer rate	Thermal Capacitor $C_t=\frac{dT}{dt}=Q$ C_t = thermal capacitance	None	Thermal Resistor $T=R_tQ$ R_t = thermal resistance

3.2 Linear Graphs

Typically, linear graphs (LGs) are applicable for lumped-parameter engineering dynamic systems[1, 2]. There, line segments (branches) are used to represent model elements. By interconnecting branches at "nodes" an LG provides a graphical representation of a model that is true to the physical structure of the modeled system. Hence, it allows visualization of the system structure prior to model formulation. As an important advantage, LGs facilitate an integrated methodology for multi-physics systems. Hence, it is a concurrent and unified approach, where all physical domains are represented in a single LG and analyzed together. In particular, in LG methodology, analogous approaches are used in modeling multiple domains. Notably, the model structure is retained across domain. Hence, interconnected components in one domain and similarly interconnected analogous elements in another domain have the same LG structure. LGs help identify similarities in the physical domain, structure, behavior, etc., in systems. Other advantages of LGs are the following. LGs facilitate the development of computer-based modeling tools and software (in systematic, unified, integrated, and graphical manner). An LG generates a unique and optimal model. Also, a different treatment is not needed when modeling multi-functional devices (e. g., a piezoelectric device, which can function as both a sensors and an actuator, can be represented simply as a reversible source). In the LG methodology, "linear" means "line," and the methodology may be used to model nonlinear systems, simply by using nonlinear constitutive equations.

As a multi-physics LG example, consider the system shown in Figure 4. It shows a DC linear motor-driven hydro-mechanical load. Hence, the system concerns the physics of electrical, mechanical, and fluid domains.

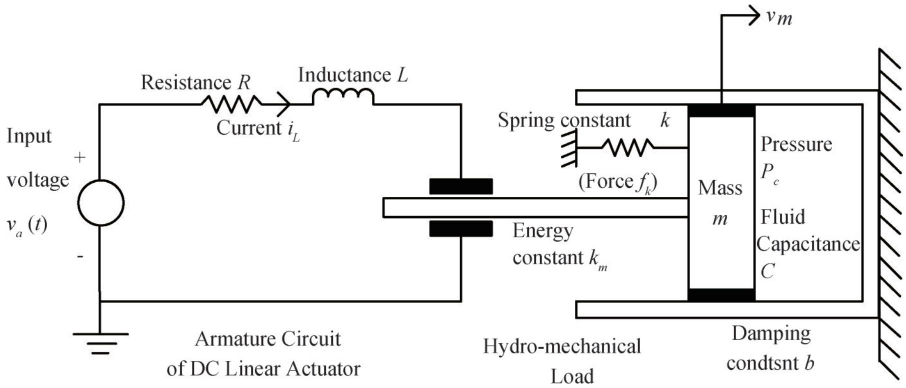

Fig.4 DC linear motor-driven hydro-mechanical load.

Its linear graph is shown in Figure 5.

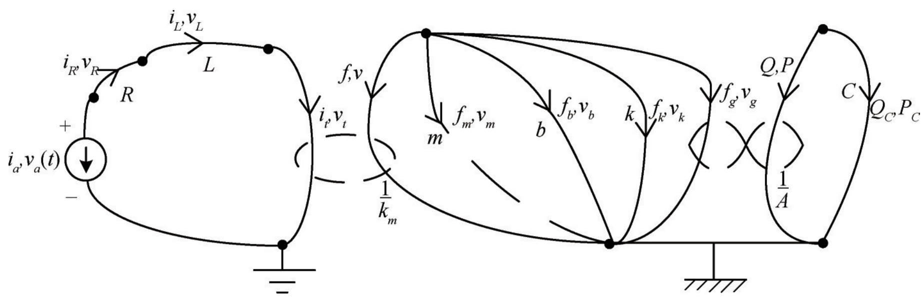

Fig.5 Linear graph model of the multi-physics system.

This system involves energy transfer between electrical and mechanical domains (which is represented by a generalized transformer) and between mechanical and fluid domains (which is represented by a generalized gyrator). This aspect of energy transfer is considered next.

3.2.1 Energy Transfer Considerations in Linear Graphs

There are two types of energy transfer (or dynamic coupling) between physical domains. One is transformer-coupling and the other is gyrator-coupling. In the first type, a generalized and ideal transformer is used. This is shown in Figure 6(a).

In this case, the across-variable of the input domain (e. g., pressure) is related to the across-variable of the output domain (e. g., velocity). Then, because of ideal energy transfer, the through-variable of the input domain (e.g., flow rate) is related to the through-variable of the output domain (e. g., force). By using these transfer relations, the two domains can be transformed into an equivalent single domain, as shown in Figure 6(b).

The other case of energy transfer involves gyrator-coupling, where a generalized and ideal gyrator is used. This is shown in Figure 7(b).

In a gyrator-coupled energy transfer, the across-variable of the input domain (e.g., pressure) is related to the through-variable of the output domain (e.g., force). Then, because of ideal energy transfer, the through-variable of the input domain (e.g., flow rate) is related to the across-variable of the output domain (e.g., velocity). By using these transfer relations, the two domains can be transformed into an equivalent single domain, as shown in Figure 7(b).

4 Equity, Diversity and Inclusion

Having presented the foundations of multi-agent systems, Mechatronics, and linear graphs, their incorporation into social systems, and particularly the use of the concepts equity, diversity, and inclusion (EDI) is established now. As discussed in[14, 15], EDI is quite important for the sustainability of a community or organization, no matter what the nature of the community or organization is. Providing opportunities to diverse members in a social group should be uniformly similar and fair. This means in a "unified," manner, in the sense of Mechatronics. Furthermore, in a social environment, equity may be implicitly enforced.

4.1 Mechatronics Viewpoint

By taking inspiration from Mechatronics, it was proposed in[15] that EDI within a community possess the conceptual analogies that are indicated in Table 3. Particular note should be made here regarding "Inclusion"

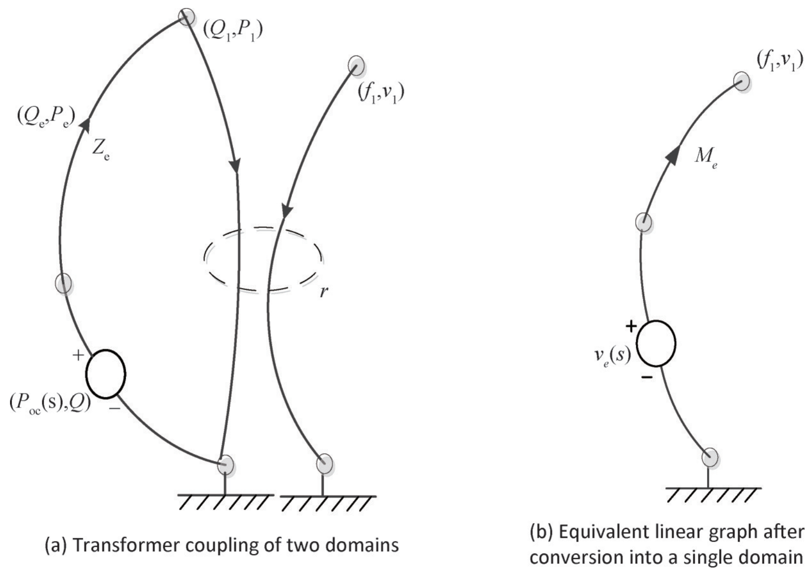

Fig.6 Transformer-coupled linear graph. (a) Transformer coupling of two domains; (b) Equivalent linear graph after conversion into a single domain.

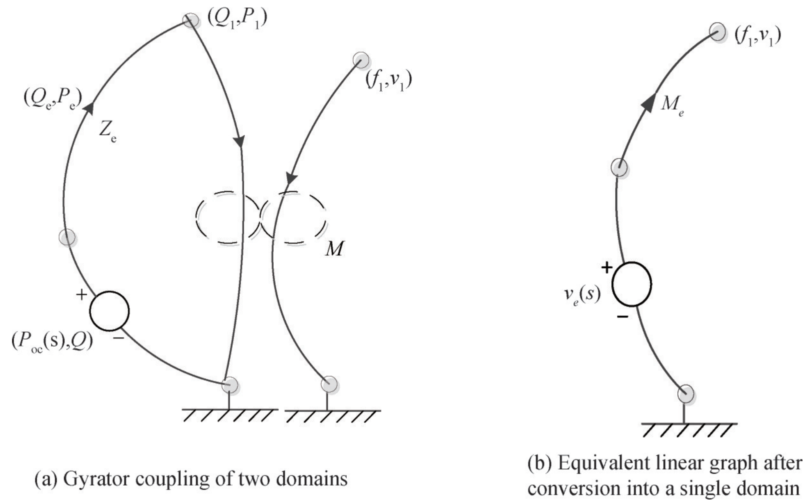

Fig.7 Gyrator-coupled linear graph. (a) Gyrator coupling of two domains; (b) Equivalent linear graph after conversion into a single domain.

in a social system, which is analogous to "Integrated Treatment" in a mechatronic system. Inclusion is not limited to allowing diverse member into the community, but also the need to pay attention to merit of the member, as needed for achieving the required goals.

Table 3 Conceptual analogy between Mechatronics and EDI.

Mechatronic System	Community
Multi-agent System	Diverse Group of People
Optimal or Unique Outcome	Equity
Unified Methodology	Diversity
Integrated Treatment	Inclusion while considering Merit as well

4.2 Application of Linear Graphs to Social Systems

Application of linear graphs, to develop an analytical model of a social system will need to first identify the necessary across-variables (analogous to velocity and voltage in engineering systems), through-variables (analogous to force and current in engineering systems), A-type elements and sources (analogous to capacitors and voltage sources), T-type elements and sources (analogous to inductors and current sources), and D-type elements (analogous to resistors). Involved across-variables may be state of wealth, happiness, health, level of education, and personal safety in society. Through-variables may be information flow, income, money flow, pollutant flow, and medicine supply. An A-type element or an A-type source may be bank account or income source. Further knowledge of this aspect can be drawn from the work of late MIT researcher Jay W. Forrester, such as Urban Dynamics[3-5] and others[20]. The elements can be either linear or nonlinear. Depending on their nature, appropriate linear or nonlinear constitutive relations should be used. Furthermore, attention has to be given to a suitable analogy in a social system, for energy transfer in an engineering system. A possible social parameter here could be "Index of Satisfaction," for both the "Donor Side" and the "Receiver Side," in a situation of financial donation. This index may be represented as the product: State of Wealth x Money Flow.

As an example, linear graph model of a community unit is shown in Figure 8. In this model, the source element is A-type, and here an income source (or any financial source) may be used. Its output is the flow of finances. The finance flow may be deposited into a bank account (an A-type element, a finance storage element or capacitor). Part of the generated finance flow may be considered to dissipate through a financial resistor, a D-type element. This element may include expenditure, taxes, and so on.

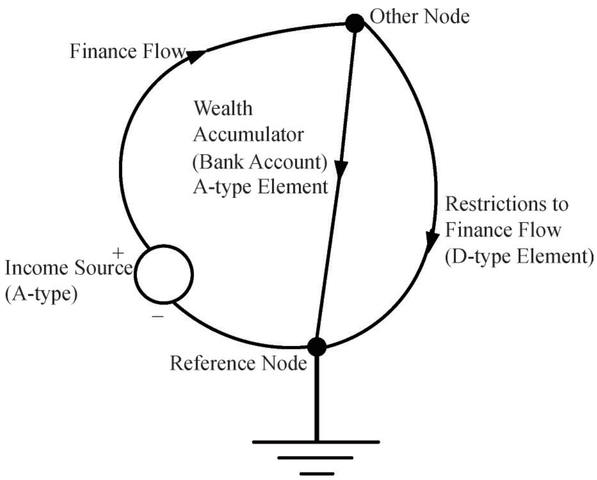

Fig.8 Linear graph model of a community unit.

4.3 Uses of an LG Model

An LG model can be used for many purposes. In the context of engineering, they may include product design and optimization, device operation and control, device analysis and simulation (before prototyping), and device testing and evaluation[1]. In particular, a design process and its outcome are field specific. In the context of engineering, these can be indicated as follows[21]: Mechanical engineers design products, manufacturing engineers design manufacturing systems (e.g., factories), electrical and computer engineers design hardware and circuits (analog and digital), and communication systems, and system architects design technical or organizational systems. In the use of analytical models, as focused in the present paper, axiomatic design[22] is quite relevant, because it establishes a scientific basis for design. Specifically, the use of analytical models for organizational mechatronic design, is the focus of axiomatic design.

Product design has been done in an ad hoc manner over the 325 years of industrial revolution[21]. Typical design steps for a product are given as[23]: Develop the design concept, develop the detail design procedure, develop the resource allocation procedure, perform cost analysis, perform product quality analysis, perform production duration analysis, and perform product planning. Note that axiomatic design establishes a scientific basis for design and optimization in any of these steps.

5 General Discussion

It is seen that a multi-agent mechatronic system possesses similarities to a social community of people. In the context of artificial intelligence (AI), Rodney Brooks [24] has recently modified the historic statement of President John F Kennedy to suit the current state of AI. The present article further adapts it as follows: "Ask not only how a properly organized community can inspire the design of a multi-agent mechatronic system, but how a properly-designed multi-agent mechatronic system can help improve the organization of a community, in meeting the requirements of equity, diversity, and inclusion."

Since the present article proposed the linear-graph approach for modeling a social system, this may be treated as "domain adaptation." Specifically, the proposed methodology considers transformation from the engineering domain into the domain of social dynamics. It is clear that other approaches of domain adaptation may be applicable as well into this problem, as given in multiple work; for example[25].

6 Conclusions

This paper presented a linear-graph approach for modeling a social system, which inherently used multi-agent Mechatronics. The main concepts of a mechatronic system, as applied in the present work, were optimal/unique outcome, unified methodology, and integrated treatment. Unified treatment meant analogous (or similar) methodology would be employed for different physical domains, when analyzing the system. Integrated treatment meant all physical domains would be analyzed together, including their interconnections and energy transfer. Two types of variables were used in this treatment. They were, across-variables, where the variable is measured across the element, and through-variables, where the variable passes unchanged through the element. Linear-graph (LG) methodology was incorporated in the present modeling approach, because it was amenable to mechatronic treatment. Specifically, the entire mechatronic system could be represented in a single LG (integrated), and analyzed using analogous methodology (unified). The LG model outcome would be unique, and hence optimal. The paper introduced multi-agent systems, which could be used to represent a social system of humans. The original definition of Mechatronics, which incorporated only the integrated design of an electro-mechanical system, was extended as needed in the present generalized treatment. The use of linear graphs in multi-physics Mechatronics was illustrated. Equity, diversity, and inclusion (EDI) as incorporated into a social system was introduced. Very importantly, the analogy between Mechatronics and EDI was proposed. Many uses of a mechatronic model were indicated. Finally, the application of Mechatronic modeling in EDI was proposed and illustrated using an LG example of a community unit.

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