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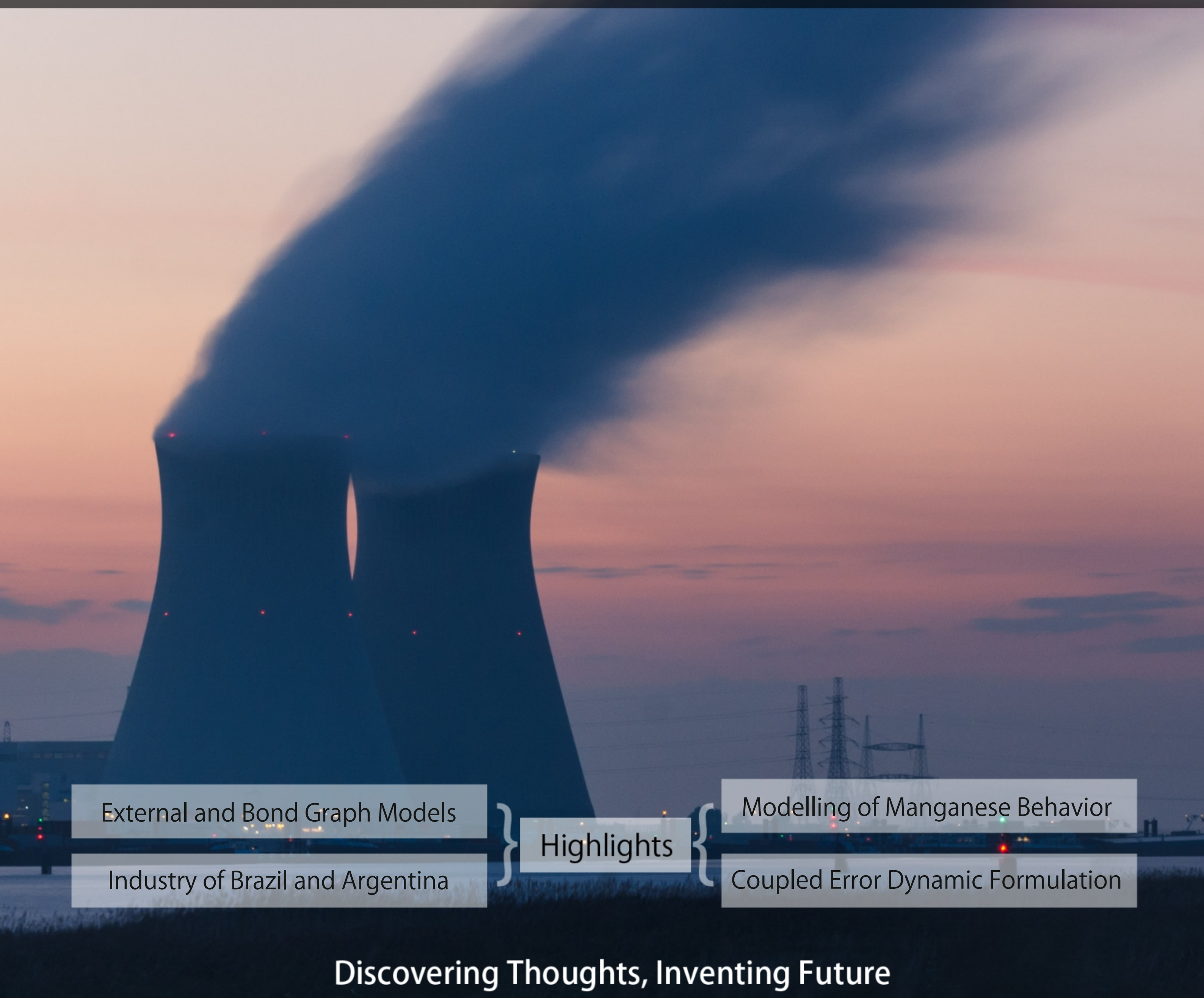

Highlights

- External and Bond Graph Models
- Industry of Brazil and Argentina
- Modelling of Manganese Behavior
- Coupled Error Dynamic Formulation

Discovering Thoughts, Inventing Future

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Thermodynamic Modelling of Manganese Behavior in Oxygen Steelmaking

By Abdelrhman Hassan, Mohammed Meraikib & Taha Mattar
Tabbin Institute for Metallurgical Studies (TIMS)

Abstract- Sufficient care is necessary to investigate slag/metal partition of manganese when the manganese content of the hot metal is higher than the optimal content of hot metal normally used for oxygen steelmaking. The slag/metal partition of manganese estimated by using the manganate capacity concept and manganous oxide activity in slag. The obtained data showed that the partial molar enthalpy of solution of MnO in the converter slag is 151 k J mol-1 and the reaction of dissolution is endothermic. The calculated activity of MnO in the slag, by using the regular ionic solution model, is largely dependent on temperature and varies only slightly with the basicity. Both the manganate capacity and distribution ratio are mainly dependent on, and inversely proportional to temperature. Specifically, manganate capacity and distribution ratio decrease only slightly with increasing basicity. The calculated distribution ratios agree well with the actual data.

Keywords: steelmaking, manganese distribution, activity of MnO, manganate capacity, slag basicity, temperature effect.

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THERMODYNAMICMODELLINGOFMANGANESEBEHAVIORINOXYGENSTEELMAKING

Strictly as per the compliance and regulations of:

Thermodynamic Modelling of Manganese Behavior in Oxygen Steelmaking

Abdelrhman Hassan [α], Mohammed Meraikib [σ] & Taha Mattar [ρ]

Abstract- Sufficient care is necessary to investigate slag/metal partition of manganese when the manganese content of the hot metal is higher than the optimal content of hot metal normally used for oxygen steelmaking. The slag/metal partition of manganese estimated by using the manganate capacity concept and manganous oxide activity in slag. The obtained data showed that the partial molar enthalpy of solution of MnO in the converter slag is 151 k J mol-1 and the reaction of dissolution is endothermic. The calculated activity of MnO in the slag, by using the regular ionic solution model, is largely dependent on temperature and varies only slightly with the basicity. Both the manganate capacity and distribution ratio are mainly dependent on, and inversely proportional to temperature. Specifically, manganate capacity and distribution ratio decrease only slightly with increasing basicity. The calculated distribution ratios agree well with the actual data.

Keywords: steelmaking, manganese distribution, activity of MnO, manganate capacity, slag basicity, temperature effect.

I. Introduction

Bahariya Iron ore which is used for sintering at the Egyptian Iron and Steel Company (EISCO) has relatively high contents of manganese, phosphorous, zinc barium, alkali chlorides and alkali oxides. In the sintering process, manganese oxides remain in the sinter that are used as blast furnace feed. Consequently, the hot metal produced contains relatively high proportions of manganese which should be brought down to the required level in the steel grade to be produced in the LD converter.

The aim of the present work is to investigate the manganese partitioning between slag and molten metal in the LD converter by using the concept of manganate capacity of slag. The effects of the main process parameters, such as temperature and slag basicity, on the factors influencing manganese distribution (i.e. activity of MnO in the slag and manganite capacity) will be studied. The data which was used for this purpose were obtained from three identical 90 ton LD converters of EISCO at Tabbin, Helwan.

II. Experimental

The trial heats were conducted on the three identical 90-ton LD converters at EISCO. At first, steel scrap was charged into the converter. This was followed by pouring the hot metal having the composition given in Table 1.

Table 1: Average composition of EISCO hot metal, weight % [1]

Element	C	Si	Mn	P	S
Composition, %	4.01	0.74	2.25	0.32	0.015

Oxygen was then blown through a water cooled lance (at a rate of 200 to 240 Nm^3/min) in the LD converter. After the start of the oxygen blowing, the first portion of burnt lime (having about 90% CaO and 2% SiO2 and/or dolomite) was fed into the converter; the rest of the fluxes were added during blowing. Due to the high content of impurities in the hot metal, double slagging technique was used. Immediately prior to slag removal, temperature was measured and a slag and corresponding metal

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samples were taken for chemical analysis. Following the removal of the first slag, oxygen-blowing was resumed and the required fluxes were added to make a fresh slag. At the conclusion of the second stage of blowing, the temperature was also measured and a slag and the corresponding metal sample were collected for analysis. Finally, the slag was removed and the steel was tapped.

The slag composition was estimated by X-ray Fluorescence technique PL72000 Model and the metal analysis was done by using an Emission Quantometer PL31000 Model. Tapped steel was then deoxidized and brought to the required composition by adding deoxidation materials and ferroalloys in the ladle [2].

III. Results and Discussion

The average analysis of hot metal used for steel production at EISCO is given in Table 1. For comparison, the range of analysis and optimal composition of hot metal normally used for steelmaking in LD converters is given in Table 2 [3].

Table 2: Range and optimal composition of hot metal for steel making in LD converter, weight% [3]

Element	**C**	**Si**	**Mn**	**P**	**S**
Range, %	3.60-4.60	0.05-2.50	0.30-3.50	≤0.30	≤0.04
Optimum, %	4.20	0.50-0.80	0.60-0.90	≤0.12	≤0.03

It is obvious that both the range and average content of manganese in the hot metal used at EISCO are higher than the average and optimal contents of manganese in the hot metal normally used for steelmaking in LD converters. The high manganese content is attributed to the high concentration of manganese oxide in the ore (MnO= 2.65%) as well as in the sinter (MnO = 2.63%) [4]. The modelling of manganese distribution between slag and metal and the main process parameters affecting the distribution are closely investigated in the present work due to the high level of manganese in the hot metal and the deleterious effect of it's control in the converter on the yield of steel.

a) Oxidation of Manganese in LD Process

The concept of manganate capacity used in this research to study the partition of manganese between slag and metal is based on the oxidation of manganese according to the reaction:

$$[Mn] + \frac{1}{2} O_{2(g)} = (MnO)_{(s)} \tag{1}$$

The equilibrium constant of this reaction, KMn, is

$$K_{Mn} = \frac{a_{(MnO)_S}}{a_{[Mn]} \cdot P_{O_2}^{\frac{1}{2}}} \tag{2}$$

where $a_{(MnO)_{(s)}}$ and $a_{[Mn]}$ are the activities of MnO in the slag and Mn dissolved in the metal respectively; P_{O_2} is the partial pressure of oxygen in the gas phase at the slag/metal interface. The equilibrium constant depends on temperature as follows [5]:

$$ln\, K_{Mn} = \frac{43463}{T} - 12.5491 \tag{3}$$

b) Activity of Manganous Oxide in the Slag

The activity of manganous oxide can be calculated by using the model of regular ionic solutions developed by Kozheurov [6,7]

$$lg\gamma_{(Fe)} = \frac{1000}{T}\left[2.18x_{Mn}x_{Si} + 5.9x_{Si}\left(x_{Ca} + x_{Mg}\right) + 10.5x_{Ca}x_P\right] \tag{4-a}$$

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$$lg\gamma_{(Mn)} = lg\gamma_{(Fe)} - \frac{2180}{T}x_{Si} \quad \text{(4-b)}$$

The ionic fraction of the cation can be calculated as follows [8]:

$$x_i = \frac{v_1}{\sum v_i \cdot n_i} \quad \text{(5)}$$

where n_i is the number of moles of cations i in 100g of the slag and v_i is the number of the cations in a molecule of the oxide.

The activity of manganous oxide can be calculated by multiplying $\gamma_{(MnO)}$ by $x_{(MnO)}$.

$$a_{(MnO)} = \gamma_{(MnO)} \cdot x_{(MnO)} \quad \text{(6)}$$

The activity is mainly influenced by temperature and slag composition.

c) Effect of Temperature on the Activity of Manganous Oxide

The activity of manganous oxide in the slag changes with the temperature as shown in Figure 1. The regression line resulting from the plotting of ln $a_{(MnO)}$ against the reciprocal of absolute temperature is straight and satisfies the formula:

$$\ln a_{(MnO)}(T) = \frac{18210}{T} - 11.478 \qquad r = 0.6737 \quad \text{(7)}$$

The correlation coefficient of equation (7) indicates moderate correlation between the activity of manganous oxide in the slag and the reciprocal of absolute temperature.

The enthalpy of dissolution of manganous oxide in the slag can be obtained from equation (7) as follows: [9,10]

$$\ln a_i = \frac{\Delta\overline{H}_i}{RT} + constant \quad \text{(8)}$$

A comparison of equations (7) and (8) leads to the following value for the relative partial enthalpy of solution of MnO in the slag of the Egyptian LD converters:

$$\Delta\overline{H}_{(MnO)} = 151.4\ kJ \cdot mol^{-1} \quad \text{(12)}$$

The positive sign of $\Delta\overline{H}_{(MnO)}$ indicates the endothermic nature of the dissolution of MnO in the slag of LD converter. This value is accepted compared with 198 k J mol^{-1} found for $\Delta\overline{H}_{(MnO)}$ in other investigations conducted by S.M.Jung et al on BOF slags[11] and 130 k J mol^{-1} found for the dissolution of MnO in lime based slags containing MnO, BaO and Na_2O [12].

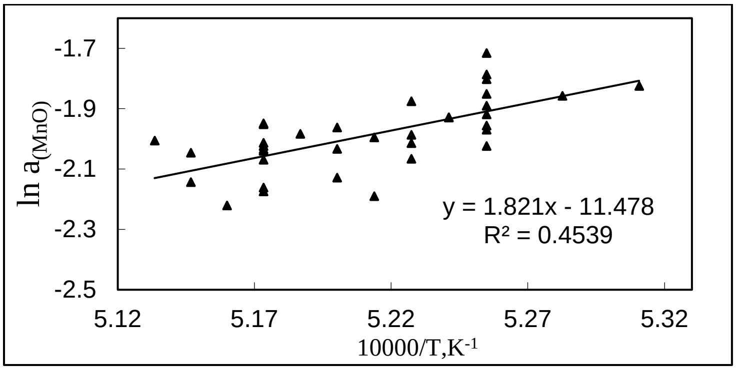

Fig. 1: Variation of the logarithm of the activity of manganous oxide with the reciprocal of absolute temperature in a narrow range of slag composition

d) Effect of Basicity and Temperature on the Activity of Manganous Oxide

In this research, the slag composition is expressed by the basicity defined in the following form:

$$B = \frac{(CaO)}{(SiO_2)} \quad (13)$$

The combined effects of basicity and temperature on the activity of manganous oxide in the slag can be estimated by plotting ln $a_{(MnO)}$ against $1/T$ at constant average basicity as shown in Figure 2. The straight lines corresponding to basicity are almost parallel. The slope depends on the temperature, whereasthe intercepts with the ordinate acquire different values at different basicities. The variation of the activityof manganous oxide with both basicity and temperature can be represented by the straight line equation:

$$\ln a_{(MnO)}(B,T) = \frac{A}{T} + b \quad (14)$$

where A is the average slope and b is the intercept of the straight line with the ordinate.

Figure 2 shows that the average slope is equal to 19,043 and the values of the intercept at different basicities are:

b=-12.004	r=0.7910	at	B=5.5099	(15)
b=-11.951	r=0.8102	at	B=6.4740	(16)
b=-11.961	r=0.9208	at	B=7.4693	(17)

Figure 3 illustrates the variation of the intercept with the basicity. The straight line can be defined by the following equation:

$$b(B) = 0.0218B - 12.1132 \qquad r = 0.7579 \quad (18)$$

Substituting the average value of the slope and the intercept $b(B)$ from equation 18 in equation 14, the following equation results for the variation of the activity of manganous oxide with both basicity and temperature:

$$\ln a_{(MnO)}(B,T) = \frac{19043}{T} + 0.0218B - 12.1132 \quad (19)$$

The equation shows the small effect of basicity against the large temperature influence on the activity.

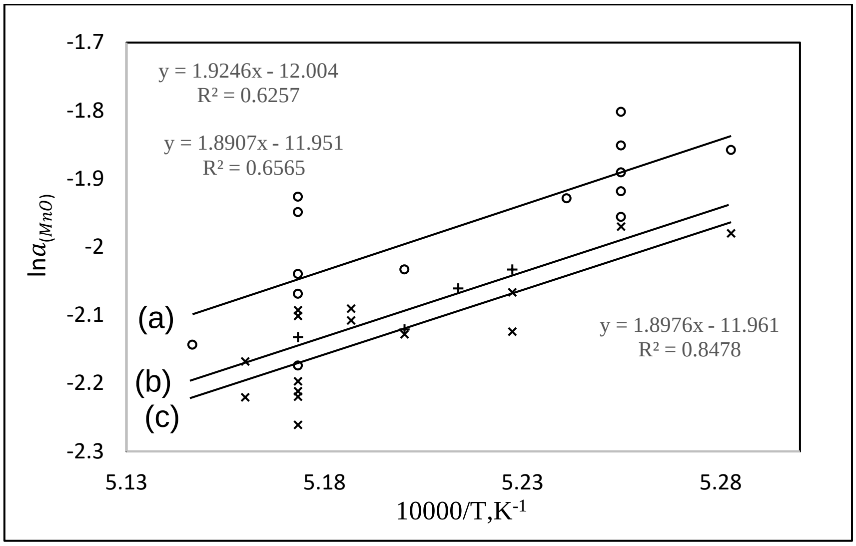

Fig: 2: Variation of the logarithm of manganous oxide activity in the slag with the reciprocal of absolute temperature at the basicity B = (a) 5.5099, (b) 6.4740 (c) 7.4693

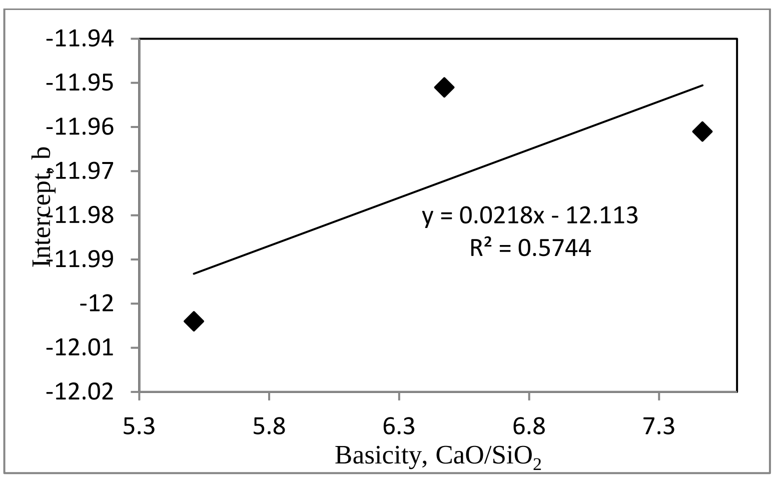

Fig. 3: Variation of the intercept, b, with the basicity, B

e) Manganate Capacity of Slag

The manganate capacity of a slag is defined as [12,13]:

$$C_{Mn} = \frac{(Mn)}{a_{Mn} P_{O_2}^{0.5}} \tag{20}$$

It is based on the oxidation reaction of manganese dissolved in the metal as given by equation (1) and it's equilibrium constant in equations (2) and (3). In order to calculate the manganate capacity, the partial pressure of oxygen is estimated from equation (2) and (3) as follows:

$$P_{O_2}^{0.5} = \frac{a_{(MnO)}}{a_{Mn} \cdot exp\left(\frac{43463}{T} - 12.549\right)} \tag{21}$$

The activity of manganous oxide in the slag can be formed by using equations (4-a and 4-b) and (6).

The activity of manganese in the metal $a_{[Mn]}$can be calculated according to the dilute solution model as follows [10,13]:

$$a_{[Mn]} = f_{[Mn]} \cdot [Mn] \qquad (22)$$

where $f_{[Mn]}$ is the activity coefficient of manganese in the metal, it can be estimated by:

$$\log f_{[Mn]} = e_{Mn}^{(Mn)}[Mn] \cdot e_{Mn}^{(O)}[O] \cdot e_{Mn}^{(C)}[C] \cdot e_{Mn}^{(S)}[S] \cdot e_{Mn}^{(P)}[P] \cdot e_{Mn}^{(Si)}[Si] \qquad (23)$$

The interaction parameters, $e_{Mn}^{(i)}[i]$ are given in table (3).

Table 3: Interaction parameters $e_{Mn}^{(i)}[i]$, [10,13]

Parameter	$e_{Mn}^{(Mn)}$	$e_{Mn}^{(O)}$	$e_{Mn}^{(C)}$	$e_{Mn}^{(S)}$	$e_{Mn}^{(P)}$	$e_{Mn}^{(Si)}$
Value	0	-0.083	-0.07	-0.048	-0.0035	0

The activity coefficient was calculated by substituting the values of the interaction parameters given intable (3) in equation (23) and the activity was found by using equation (22).

f) *Effect of Basicity and Temperature on Manganate Capacity*

The combined effects of both slag basicity and temperature on the manganate capacity can be estimated by plotting ln C_{Mn} against ${}^{10000}/_{T}$ at constant average basicity $B = \frac{(CaO)}{(SiO_2)}$ as in the case of the activity of manganous oxide. This is illustrated in Figure 5. The group of straight lines corresponding to basicity are parallel.

Their slope depends on temperature, where the intercepts with the ordinate have different values depending on the basicity. As in the case of activity, the variation of the manganate capacity with both basicity and temperature can be represented by the equation:

$$\ln C_{Mn}(B,T) = \frac{M}{T} + d \qquad (24)$$

Where M and d represented the average slope of the straight lines and the intercept of each line with the ordinate, respectively.

The straight lines in Figure 4, relating to the basicity B, have an average slope equal to 37341. The values of intercept, d, at different basicities are as follows:

$d(B) = -4.9307$ r=0.9861 at B=5.5006 (25)

$d(B) = -4.9819$ r=0.9907 at B=6.0162 (26)

$d(B) = -5.0454$ r=0.9628 at B=6.4722 (27)

$d(B) = -5.3705$ r=0.9643 at B=6.9812 (28)

$d(B) = -5.389$ r=0.9565 at B=7.4501 (29)

$d(B) = -5.5102$ r=0.9880 at B=8.0049 (30)

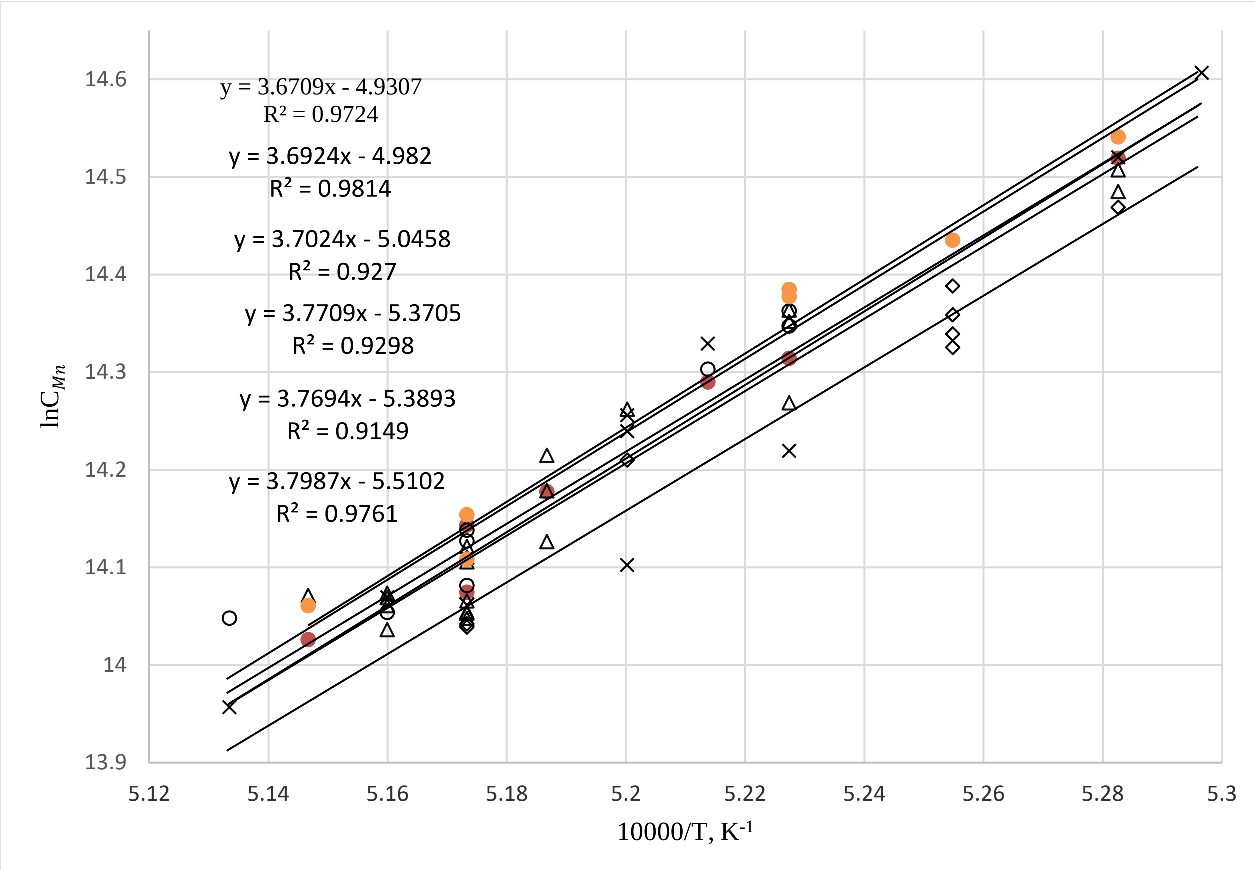

Fig. 4: Variation of the logarithm of manganese capacity in the metal with the reciprocal of absolute temperature at the basicity B = (a) 5.5006, (b) 6.0162, (c) 6.4722, (d) 6.9812, (e) 7.4501, (f) 8.0049

The intercept varies with the corresponding values of basicity as shown in Figure 5, which can be described by the following formula:

$$d(B) = -0.2564B - 3.4774 \qquad r = 0.9621 \tag{31}$$

Substituting the average slope and the intercept from equation (31) in equation (24), therefore thecombined effects of basicity and temperature on the manganate capacity can be expressed as:

$$\ln C_{Mn}(B,T) = \frac{37341}{T} - 0.2564B - 3.4774 \tag{32}$$

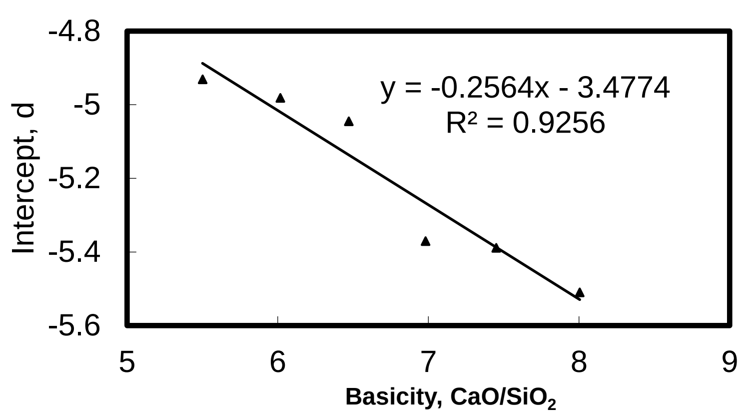

Fig. 5: Variation of the intercept, d, with the basicity, B

g) Manganese Partitioning between Slag and Metal

Substituting the partial pressure of oxygen in equation (21) from equation (2), the definition of manganatecapacity can be defined as:

$$C_{Mn} = \frac{(Mn)\cdot K}{a_{(MnO)}} \tag{33}$$

The distribution ratio of manganese between slag and metal is defined as:

$$\eta_{Mn} = \frac{(Mn)}{[Mn]} \tag{34}$$

It follows from equation (33) and (34) that:

$$\eta_{Mn} = \frac{C_{Mn}\cdot a_{(MnO)}}{K\cdot [Mn]} \tag{35}$$

As in the case of manganate capacity, the distribution ratio is also affected by slag basicity and temperature.

h) Effect of Basicity and Temperature on Manganese Distribution

The combined effects of basicity and temperature on the manganese distribution ratio can be found by substituting the manganate capacity and manganous oxide activity in equation (35) by the corresponding equation showing the combined effects of basicity and temperature. It follows from equations (19) and that:

$$\eta_{Mn}(B,T) = \frac{e^{\left(-0.2346B+\frac{12921}{T}-3.0415\right)}}{[Mn]} \tag{38}$$

The results obtained by using this equation to calculate the manganese distribution ratio are illustrated in Figure 6, which are as follows:

$$\eta_{Mn(cal)} = 1.033\cdot\eta_{Mn(obs)} \qquad r = 0.889 \tag{39}$$

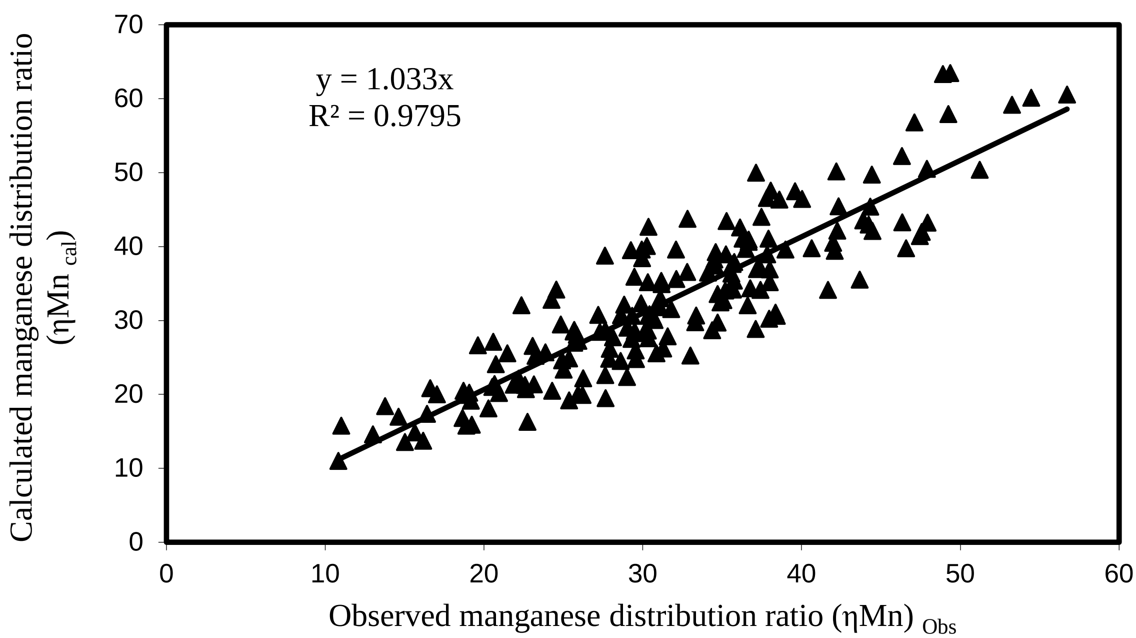

Fig. 6: Relationship between calculated and observed manganese distribution ratio between slag and liquidsteel in oxygen steelmaking processes

IV. Conclusions

The data were used to investigate the effects of temperature and slag composition on the activity of manganous oxide in the slag and manganate capacity, the data were then utilized for the estimation of the slag/metal distribution ratio of manganese. The following conclusions can be made:

1. The partial molar enthalpy of solution of MnO in the converter slag is 151 k J mol^{-1} and the reaction of dissolution is endothermic.
2. The activity of MnO is largely dependent on temperature and changes only slightly with the basicity of the slag.
3. The manganate capacity is mainly dependent on, and is inversely proportional to, the temperature; it is slightly affected by basicity.
4. The distribution of manganese between slag and metal can be calculated by using the manganate capacity. In addition, it was found that the calculated distribution ratios agree well with the observed data.

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Supervision and Control Industrial Refrigerator by Integration External and Bond Graph Models

By Abderrahmene Sallami & Maher Ben Hariz
University of Tunis

Abstract- This article aims to solve the problems of supervision and PI controller of an industrial thermal system (the industrial static refrigerator). The structure of an industrial system from the point of view of the external model operates in several modes of operation (normal and abnormal). For this external model, we have two problems, the first problem is a fault location problem because we are talking about a global operation of the system and the second problem is a problem of visualization of the phenomenon of switching between the operating modes of the system. For this, in this article we have integrated two other models to solve the problems in question. For the localization problem, we used the bond graph model. This model, by its graphic nature and the use of a unified language, allows to model the industrial system element by element from which it helps the user not only to detect defects, but also to locate them when they appear in the system.

Keywords: supervision system, PI controller, bond graph model, external model, normal and abnormal, industrial refrigerator.

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Abderrahmene Sallami [α] & Maher Ben Hariz [σ]

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Keywords: supervision system, PI controller, bond graph model, external model, normal and abnormal, industrial refrigerator.

I. Introduction

Today, we find that industrial systems are becoming more complex. This complexity requires the enlargement of the traditional model; so far this model is limited to control algorithms. The supervisory design of these systems must be evolved to take into account several valuable information processing systems (sensors and actuators) for which decision making is inevitable. This evolving needs and technological progress made in the field of sensors, actuators and communication field bus lead to the design of the supervision system has used intelligent systems (sensors and actuators) that incorporate a very large information capacity with automated process.

In this context several works have been carried out to provide the object-oriented functional (model external) and behavior (object-oriented model) functions to analyze the design of the intelligent equipment supervision system (Jinghao et al., 2018; Praveen et al., 2018; Andrei, 2015; Merzouki et al., 2013; Chatti et al., 2013; Khalil et al., 2012; Loureiro et al., 2012; Bera et al., 2012; Samantary et al., 2008). As far as the external model is concerned, this model uses the concepts of services, missions and mode of operation which offer to the user organizations based on modes of operation information on the behavior of the component in different operating situations (normal or defective).

The disadvantage of the external model is that it describes the industrial system in terms of functions, without taking into account parameters of physical and dynamic behavior. This consideration leads to certain ambiguity such as the location of defects. This is why the leap-graph model as a graphical modeling language of industrial systems element by element is a practical and useful complementary tool for obtaining behavioral and diagnostic models. In addition, the causal properties of this model can help design FDI (Fault Detection and Isolation FDI) algorithms (Raghappriya and Kanthalakshmi, 2020; Jayaprasanth and Kanthalakshmi, 2018; Flett and Bone, 2016; Ahmed et al., 2013; Simani, 2006; Medjaher et al., 2006; Chen and Lee, 2002; Graisyhm, 1998; Duthoit; 1997; Staroswiecki, 1994; Cassar et al., 1994).

This integration allows us to obtain behavioral knowledge about intelligent industrial systems, but it is limited since switching between modes is not determined. For this article is determined, hence the contribution of this article is to use the transfer function model to determine the output dimmer in each operating mode of the industrial system by inserting a switching program between the operating modes according to the necessary tipping conditions. In this way, it becomes possible to obtain, on the one hand, the behavioral knowledge of the intelligent industrial system for monitoring in case of faults and, on the other hand, to see the switchover between the modes of operation; and therefore, to ensure a modernized security standard.

In this article, the work is distributed as follows; the first section focuses on the concept of the supervisory system and these advantages in the automation of industrial systems. The second section will be determined on the concept of the external model and these advantages and disadvantages to describe

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an industrial system. The third section a brief introduction to the bond graph model in the interest of monitoring industrial systems, then the method of integrating the bond graph model with the external model, to complete the description of the industrial system is explained. In the fourth section we will use the concept of the bond graph transfer function model to determine the tilting of the operating worlds of the industrial system. Then, the design of PI controllers for each operating mode is proposed (Jeyashanthi and Santhi, 2020; Čedomir et al., 2019; Kalaivani. and Lakshmi, 2014; Lutfy, 2010). Finally, a conclusion to illustrate all the work we have done.

II. Supervision by External, Bond Graph and Transfert Function Models

a) *Supervision System*

Supervision is generally defined as a task of controlling and monitoring the execution of an operation or work performed by other agents (men or machines), without going into the details of this execution. We have adopted the definition of the Research Group on Integrated Automation and Human Machine-Driven Systems, which stipulates that: supervision is the set of tools and methods used to conduct industrial installations both in normal operation and in the event of faults or disruptions for industrial system see figure 1.

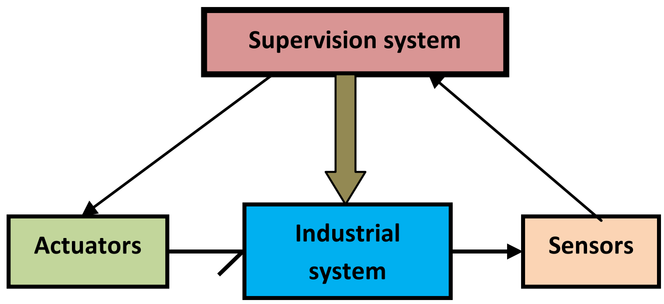

Fig. 1: Supervision System for industrial system

A supervisory system is active if it gathers all the events necessary to activate the decision-making see figure 1:

- *Real-time:* Decision-making will be effective and fast if the situational awareness is complete.
- *In delayed time:* Decision-making will be taken as appropriate and the analysis of concrete situations allows a formalization of the operations to be created for each provision.

A supervisory system can improve the process with:

- Continuous use of the system (no interruption),
- Minimization of fault tripping (speed and reliability),
- Optimization of the use of system components,
- Minimization of maintenance costs,
- Realization of benefits for industrialists (economic).

b) *External Model*

Industrial systems consist of a set of interconnected equipment. A hardware failure of one or more of these devices may jeopardize the achievement of some of the objectives for which the system was designed, so users should be warned by generating alarms. The latter must be sufficiently synthetic to express clearly the nature of the failure and its consequences. Research has developed modeling by external model (Sellami et al., 2018; Sallami et al., 2016; Imhemed et al., 2007; Maza et al., 2006; Bayart et al., 1998; Bayart et al., 1999).

This model is based on the following notions:

- Concept of services,
- Concept of missions,
- Concept of operating modes.

Industrial systems consist of a set of equipment (heat exchanger, motor, pump, etc.) that are organized in such a way that the systems can meet the objectives for which they were designed. These devices are arranged in two ways:

- *Low level:* These are basic services; they are directly interfaced with the process (valves, tank, sensors...).
- *High level:* These are composed services; they consist of basic services (cooling circuits, water booster unit, desalination unit...).

Elementary services (of low level) are associated with each other to define so-called composite services; the latter realize what we call a mission. A hardware failure means the unavailability of certain basic services and may call into question the continuation of certain missions.

The missions were the first to take responsibility for managing and managing systems in accordance with the objectives of the specifications. But at a given moment, only a subset of these missions is necessary to meet the objectives set. Each of these subsets is referred to as the operating mode.

An operating mode (*MEi*) corresponds to a set of service versions represented by Si, this set is the grouping of the subsets that define the desired operating mode, so we have the following relation: $MEi = \{S_1, S_2......, S_n\}$.

At a given moment, the process is executed in an operating mode (represented by *MEi*), all the operating modes are available and interconnected to perform what we call operating mode management graph.

The request to change from one mode to another mode must be indicated for safety reasons because the system may fall on an operating mode *MEj* which is not available, hence the necessity of having a logical passage that leads The system on a mode of operation without getting into trouble. This passage is represented by a Boolean variable *bij*. The set of operating modes and the conditions of passage *bij* are described by a graph of management of the operating modes and which can be represented in figure 2.

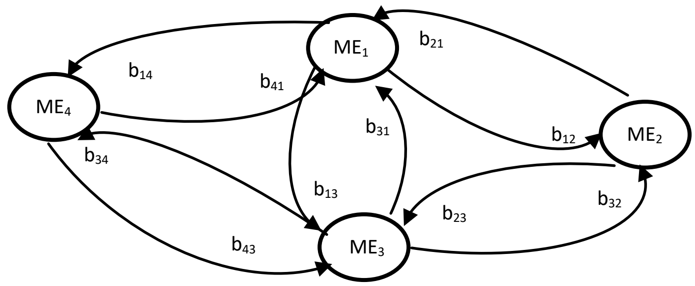

Fig. 2: Operating mode management graph

c) Bond Graph Model

The bond graph modeling tool was defined by Henry Paynter (Henry, 1961), it is a language of graphical representation of physical systems, based on the modeling of the energy phenomena intervening within these systems. This energetic approach makes it possible to underline the analogies that exist between the different fields of physics (mechanics, electricity, hydraulics, thermodynamics, acoustics, etc.) and to represent in a homogeneous form the multidisciplinary physical systems . In this article, we will present the utility of the bond graph tool for the supervision of industrial systems. In the first part we will give the different approaches using the bond graph for the design of a supervisory system (qualitative and quantitative approach), the second part is devoted to the integration of the external model and the bond graph model for the supervision systems (Joel and Christophe, 2018; Montazeri et al., 2018; Tapia et al., 2018; Nacusse, et al., 2015; Ould-Bouamama, 2014; Ould-Bouamama, 2013; Samantaray and Ould Bouamama, 2008; Benmoussa et al., 2012; Aitouche et al., 2008).

Bond graph based modeling relies mainly on the concept of generalized stress and flux variables that allow the representation of balance sheets and energy exchanges between different elements of a system. In this approach, an energy exchange between two elements is represented by a half-arrow link indicating the direction of the transfer. These half-arrows are called "leaps", each is labeled by a force variable e and a flux variable f. The product of these two variables corresponds to the power "carried" by the leap. This power is counted positively in the direction of the half-arrow. The advantage of this modeling is that the choice of e and f depends only on the physical domain of the system to be represented in figure 3.

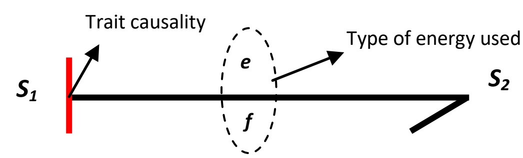

Fig. 3: Representation of a physical system by bond graph

This description is made in terms of components connected together by links through the ports they have, the components are classified by the number of ports they have, they are multiport or n-ports as described in. There are three types of Bond Graphs each used in a particular stage of the design process [22-28]:

- Bond Graphs with words where the components represent subsystems described by black boxes, this level allows a first decomposition of the system to have an overall view of the energy exchanges implemented;
- Bicausal Bond Graphs where the components are indivisible elementary components and whose behavior is known (resistance, inductance, capacitor, etc.), this level is used at an advanced stage of the design process, where the components can be assimilated Perfect elementary components;
- Causal Bond Graphs which allow establishing the equations of the system.

In the sense of bond graphs, the services provided by the equipment of energy sources of the mechanical (motor), thermal (thermo resistance, potential energy or kinetic of a fluid) and hydraulic (pump) type energy sources are represented by sources of energy, Effort *Se* (*MSe*) or flow *Sf* (*MSf*). The services provided by the functional role of the equipment (storing, transforming, transporting, etc.) are designated by the leaf graph elements *R*, *C*, *TF* and *GY*. The services offered by the sensors (measurements) are ensured by the force (*De*) and *flow* (*Df*) detectors, the requests associated with these services are modeled by information links.

It should be noted, however, that the leap graph services can be quantified by constitutive equations of the modeled leap graph elements. Missions represented by sets of the highest level services as defined in the external model must satisfy all the objectives set out in the specification and are of course based on the services offered by the lower level equipment.

At all times, an installation operates in an operating mode whose behavior is described by a bond graph model. Thus, each mode of operation (*MEi*) corresponds to a bond graph *MBGi* model represented by figure 4.

If *Si* is the set of jump graph elements and Vi is the version of each set, then the jump graph model is the sum of these sets associated with the *MEi* mode, ie the following relation: $MBGi = MEi = \{S_1(V_1)\ ,\ S_2(V_2)\ ...,\ S_n(V_n)\}$.

The bond graph *MBGi* models of the system are linked by bij transitions, for each two jump graph models there are corresponding transition elements specific to them, for example in figure 3, the pattern graph respectively MBG_2 and MBG_3 are linked by the transition elements b_{23} and b_{32}.

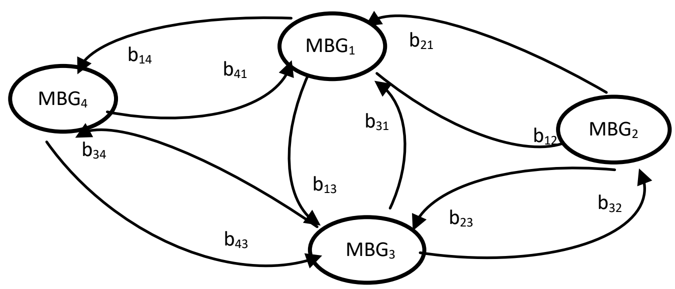

Fig. 4: Management graph of the *MBGi* using *MEi*

From the point of view of industrial process monitoring, the causal properties of the bond graph are used for the detection and isolation of faults affecting the sensors, actuators or physical components of the process. Thus, the availability of the services (necessary for the realization of a mission) will be provided by the monitoring algorithm to the graph of management of operating modes.

d) Transfer Function Model

Most physical systems can be described as operations that map responses from an input. These operations are transfer functions that explain the patterns of behavior between inputs and outputs. These transfer functions are obtained from linear or non-linear differential equations and can be in the form of a diagram containing all the information needed to simulate the system as a whole. At any time, the physical systems can operate in an operating mode whose behavior is described by a bond graph model (*MBGi*) corresponds to a transfer function model (*MFTi*) represented by figure 5.

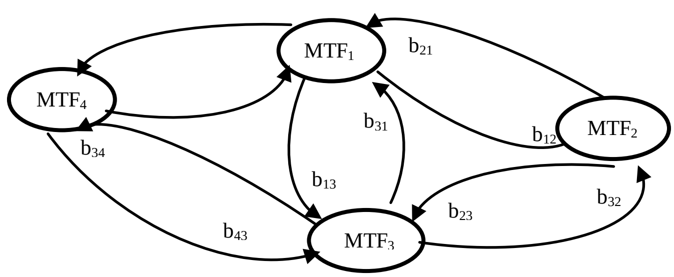

Fig. 5: Management graph of the *MTFi* using *MBGi*

Starting from the causality of each element of the bond graph model of a system, we will replace each element of this bond graph model with a basic functional schema. Indeed, each link of the model bond graph carries two signals the flow and the effort must represent by a full arrow each of the signals (f, e) associated with each link. The table 1 below shows the passage of each element of the bond graph model to the block diagram.

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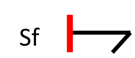
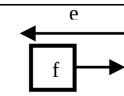
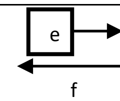
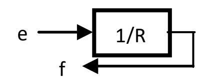
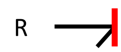
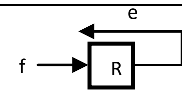
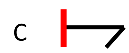
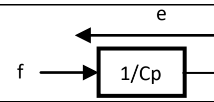
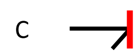
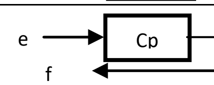
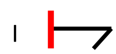
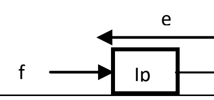
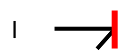
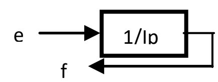
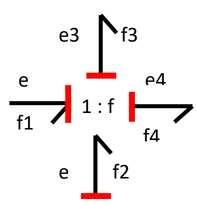
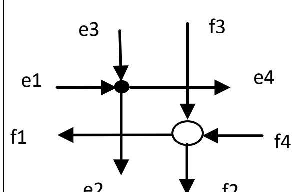
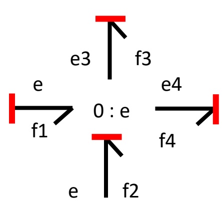
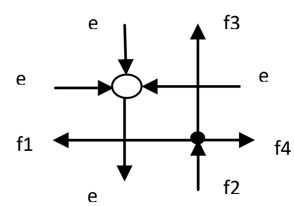
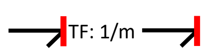
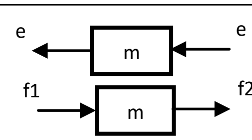
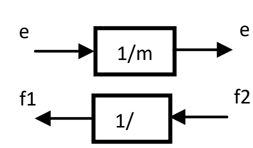
Table 1: Transfer function model of the basic elements

Elements	Bond graph model	Function transfer model
Flow source		
Effort source		
Restriction element		
		
Capacity element		
		
Inertial element		
		
Junction 1		
Junction 0		
Junction TF		
		

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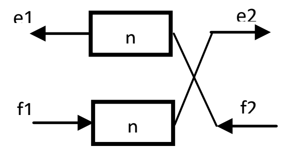
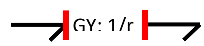
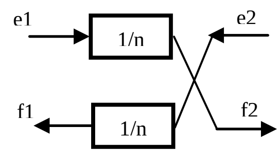
Junction GY		
		

The transition from the bond graph model to the functional diagram is done in a systematic way by following the following steps:

- Change the bonds of the bond graph model into two signals (flow and effort);
- Replace each junction 1 (respectively junction 0) in an algebraic sum of forces (respectively flow);
- Taking into account the causality of each element of the bond graph model, replace each element with the corresponding transfer function;
- Rearrange the functional diagram obtained to place the input and output variables;
- Simplify the functional diagram;
- Calculate the transfer function.

III. Supervision and Control of Industrial Refrigerator

In this article, we will use the domestic static refrigerator to develop our contribution. This refrigerator is equipped with freezer and a cooling compartment. The volume of behavior is 150 L with two plastic containers containing water and ice. Our work in this article focuses on heat transfers in the refrigerator compartment (see figure 6) (Sellami, 2018).

a) *External Model of Industrial Refrigerator*

The industrial refrigerator provides cooling of the air and fulfills the following tasks:

- Mission 1: Check for leaks at the heat exchanger;
- Mission 2: Check the seal at the refrigerator door;
- Mission 3: Check for ice water leaks;
- Mission 4: Check for leaks at the water tank;
- Mission 5: Ensure the cooling of the auxiliaries using only the cold heat exchanger with the presence of the water tank and iced water;

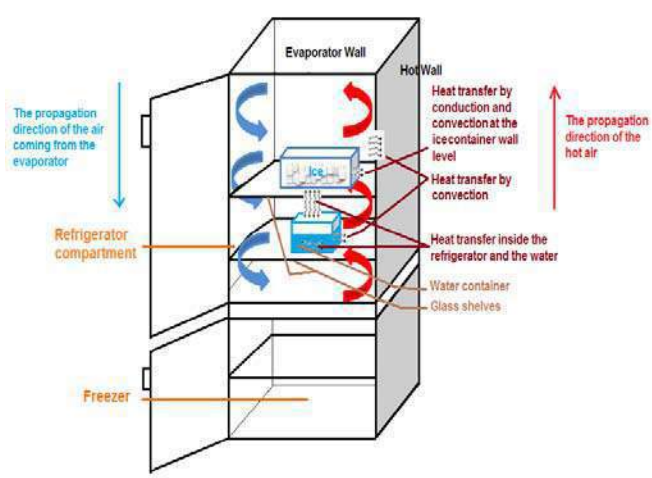


Fig. 6: Static refrigerator with heat transfers

- Mission 6: Ensure the cooling of the auxiliaries by using the cold water exchanger without iced water;
- Mission 7: Provide cooling of the auxiliaries using the cold water exchanger only;
- Mission 8: Shut down the system and empty it.
- Mission 9: Maintain the entire system circuit.

The tasks of the industrial refrigerator are those that are responsible for the management and management of the system in accordance with the objectives of the specifications. Indeed, at a given moment, only a subset of these missions is necessary to achieve the set objectives. Each of these subsets is called the operating mode.

For this cooling system, there are three modes of operation:

- Nominal operating mode: the refrigeration is ensured by two elements (the exchanger of cold and chilled water);
- Mode of operation without iced water: the refrigeration is ensured by a single element (the exchanger of cold);
- Mode of operation without water: the refrigeration is ensured by a single element (the exchanger of cold);
- Complete shutdown mode: the cooling air flow is stopped and maintenance can be ensured.

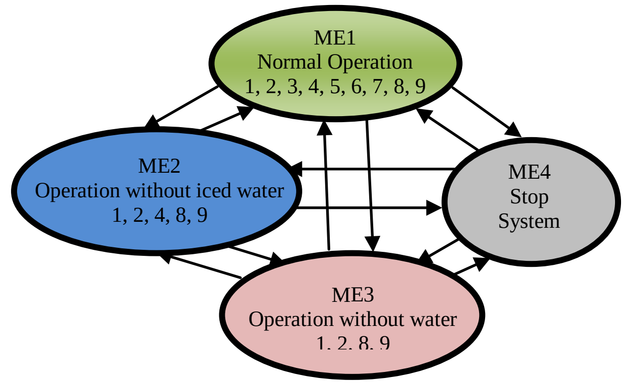


Fig. 7: Different functions of the industrial refrigerator

In case of hardware failure, the industrial refrigerator becomes unable to continue part of the missions for which it was designed. Operators of driving and maintenance must be informed. Manufacturers of the industrial refrigerator combine four (04) alarms. They are illustrated in table 2. This table gives for each defect a list of services and missions.

Table 2: Consequences of defects on the availability of services and missions

Alarmes	Defaults	Service Level 0	Service Level 1	Missions
A-01	Leak exchanger level	No cooling	Reduced cooling	1, 7
A-02	Leak door level	No sealing	Bad seal	2
A-03	Leak iced water level	Not iced water	Reduced iced water	3
A-04	Leak water level	No water	Reduced amount of water	4

Alarm A-01: This fault is associated with the leakage at the level of the exchanger of the industrial refrigerator, the mission concerned with this element are 1 where operating modes are threatened ME_1, ME_2 and ME_3. The absence of these missions makes the modes in question unavailable. If the normal operating mode (or the operation mode without ice, or the operating mode without a water tank) is the current mode, in the event of a fault, the automatic changeover to another mode must be taken into account. In this case, we find that the available mode is the stop mode ME_4.

Alarm A-02: This fault is associated with the leak at the door level, the mission concerned with this element is the mission 2 from which the operating modes are threatened ME_1, ME_2 and ME_3. The absence of this mission makes the modes in question unavailable. If the normal operating mode (or the operation mode without ice, or the operating mode without a water tank) is the current mode, in the event of a fault, the automatic changeover to another mode must be taken into account. In this case, we find that the available mode is the stop mode ME_4.

Alarm A-03: This fault is associated with the leak at the level of the chilled water, the mission concerned with this element is 3 where mode of operation is threatened ME_1. The absence of these missions makes the modes in question unavailable. If the normal operating mode ME_1 is the current mode, in case of a fault, it is necessary to take into account the automatic changeover to another mode. In this case, we can switch to the other modes ME_2, ME_3 or ME_4.

Alarm A-04: This fault is associated with the leakage at the water level, the mission concerned with this element is the missions 4 the operating modes are threatened ME_1 and ME_2. The absence of these missions makes the modes in question unavailable. If the normal operating mode is the current mode, in the event of a fault, it is necessary to take into account the automatic changeover to another mode. In this case, we find that the two available modes are ME_3 or ME_4.

b) Bond Graph Modeling Treatment

In this mode of operation ME_1, the refrigeration of the auxiliaries is ensured by the circulation of the air through two elements (the exchanger of cold and iced water);

The model of the bond graph MBG_1 corresponds to figure 10 which corresponds to the modeling of the dual flow air treatment unit.

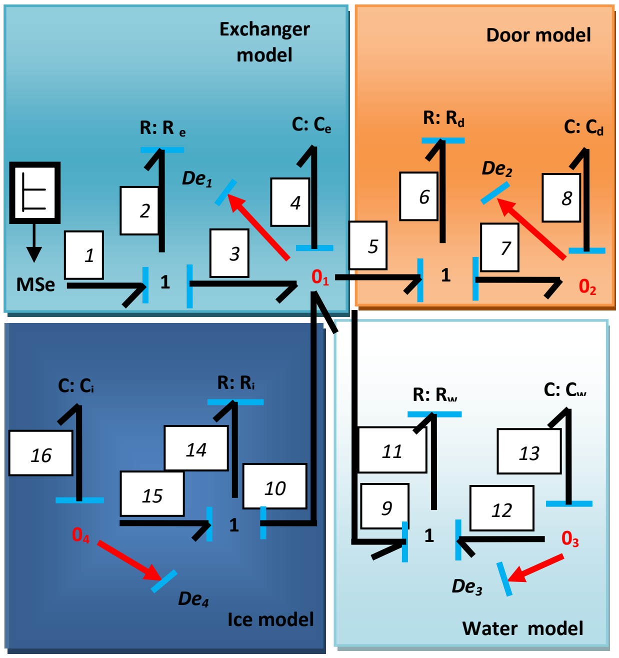


Fig. 8: Bond graph model in normal operation MBG_1

In this mode of operation ME_2, operation with a single element (the heat exchanger). The bond graph model for this (MBG2) can be easily deduced, then we obtain the link graph model shown in figure 9, which corresponds to the modeling of the industrial refrigerator with the cold heat exchanger only.

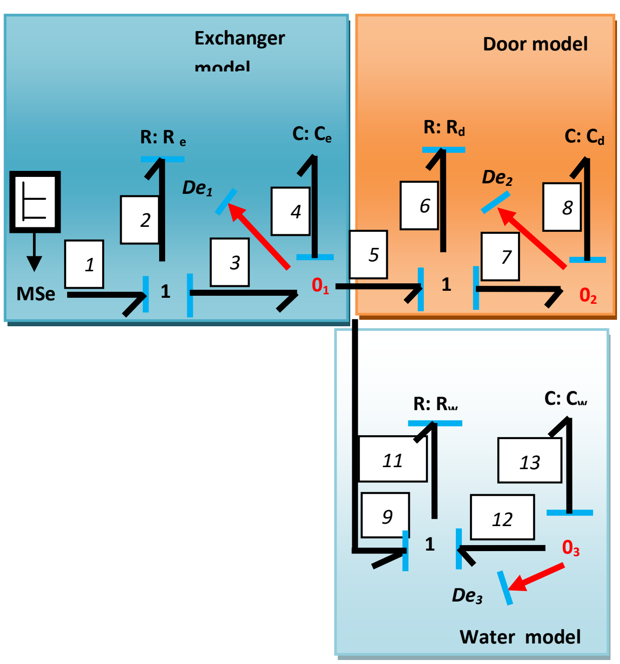


Fig. 9: Bond graph model operation without iced water MBG_2

In this mode of operation ME_3, operation with a single element (the heat exchanger) and also without water. The bond graph model for this MBG_3 can be easily deduced, and then we obtain the link graph model shown in figure 10, which corresponds to the modeling of the industrial refrigerator with the cold exchanger only and without the model of the water.

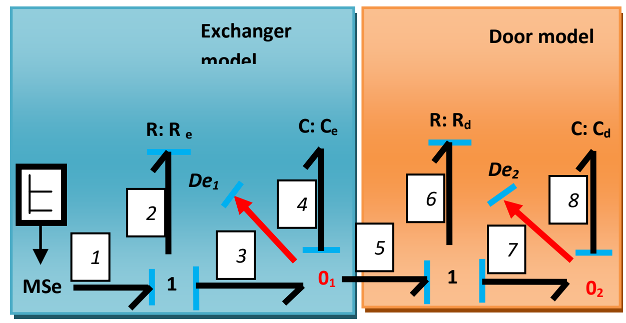


Fig. 10: Bond graph model operation without water MBG_3

To determine the residues using the redundant analytical relationship method. In our case we will change the temperature sensors (De_1, De_2, De_3 and De_4) by residues (r_1, r_2, r_3 and r_4) which are at the junctions 0_1, 0_2, 0_3 and 0_4.

✓ For the junction ''0_1'', the conservation relation is:

$$f_3 - f_4 - f_5 + f_9 - + f_{10} = 0$$

- $f_3 = \frac{1}{R_e}(MSe - De_1)$
- $f_4 = C_e \frac{dDe_1}{dt}$
- $f_5 = \frac{1}{R_d}(De_1 - De_2)$
- $f_{\varsigma} = \frac{1}{R_w}(De_1 - De_3)$
- $f_{10} = \frac{1}{R_i}(De_1 - De_4)$

The first residual r_1 can be written as:

$$r_1 = \frac{1}{R_e}(MSe - De_1) - C_e \frac{dDe_1}{dt} - \frac{1}{R_d}(De_1 - De_2) - \frac{1}{R_w}(De_1 - De_3) - \frac{1}{R_i}(De_1 - De_4) \quad (1)$$

✓ For the junction ''0_2'', the conservation relation is:

$$f_7 - f_8 = 0$$

- $f_7 = \frac{1}{R_d}(De_1 - De_2)$
- $f_4 = C_d \frac{dDe_2}{dt}$

The first residual r_2 can be written as:

$$r_2 = \frac{1}{R_d}(De_1 - De_2) - C_d \frac{dDe_2}{dt} \qquad (2)$$

✓ For the junction ''0_3'', the conservation relation is:

$$f_{13} - f_{12} = 0$$

- $f_{13} = C_w \frac{dDe_3}{dt}$
- $f_{12} = \frac{1}{R_w}(De_1 - De_3)$

The third residual r_3 can be written as:

$$r_3 = \frac{1}{R_w}(De_1 - De_3) - C_w \frac{dDe_3}{dt} \qquad (3)$$

✓ For the junction ''0_4'', the conservation relation is:

$$f_{16} - f_{15} = 0$$

- $f_{16} = C_i \frac{dDe_4}{dt}$
- $f_{15} = \frac{1}{R_i}(De_1 - De_4)$

The fourth residual r_4 can be written as:

$$r_4 = C_i \frac{dDe_4}{dt} - \frac{1}{R_i}(De_1 - De_4) \qquad (4)$$

The residues are grouped with the elements of the industrial refrigerator in table 3. We obtain a boolean matrix (0 or 1). The columns are associated with the residues r_1, r_2, r_3 and r_4 and the lines are the fifteen elements.

Table 3: Matrix of faults signatures for the industrial refrigerator

	r_1	r_2	r_3	r_4
F_1:MSe	1	0	0	0
F_2:Ce	1	0	0	0
F_3:Cd	0	1	0	0
F_4:Ci	0	0	0	1
F_5:Cw	0	0	1	0
F_6:Re	1	0	0	0
F_7:Rd	1	1	0	0
F_8:Ri	1	0	0	1
F_9:Rw	1	0	1	0
F_{10}:De1	1	1	1	1
F_{11}: De2	1	1	0	0
F_{12}: De3	1	0	1	0
F_{13}: De4	1	0	0	1

According to this table 3, we can note that the elements F_1, F_2, F_3, F_4, F_5 and F_6 are sensitive by a single residue. While the elements F_7, F_8, F_9, F_{10}, F_{11}, F_{12} and F_{13} have several residues that are sensitive. To solve this monitoring problem, a linear combination of these different residues with other residues is necessary to eliminate some redundant variables.

i. *Normal Operation*

In this mode of operation the industrial system operates under the favorable conditions where the trend of the residues converges towards zero (figure 11) and the temperature curves indicate the following values Te = 0 C, Td = 25 C, Tw = 25 C et Ti = 0 C (figure 12).

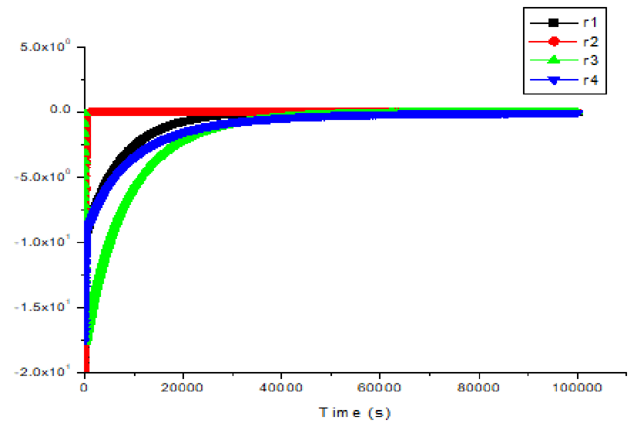


Fig. 11: Evolution of the residues in normal operation

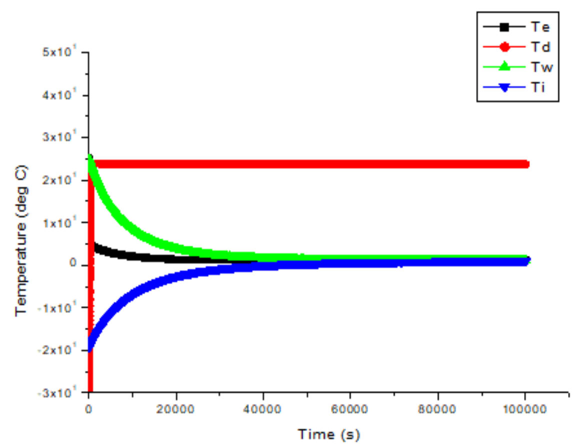


Fig. 12: Evolution of the temperatures in normal operation

i. *Abnormal Operation*

In this mode of operation the industrial system operates in unfavorable conditions from where the residues do not converge towards zero and the temperature trends indicate new values. To analyze this system we will insert four faults (four alarms).

Alarm 01: This fault corresponding to a fault (leakage) of the exchanger of the industrial refrigerator modeled by the element *Ce*, this fault causes a decrease in the amount of cooling potential (Figure 14). This element exists in the equation of the residue r_1 for each operating mode MBG_1, MBG_2 and MBG_3 (figure 13), from which only the residue r1 is sensitive to this defect in accordance with the table 3 of signature of the defects (this defect is localized by this residue r_1). However, if this component is defective, all operating modes are affected. Therefore, switching to other modes of operation is not allowed because this element exists in operation mode without chilled water and in operating mode without water tank. In this case, the available mode is the stop mode MBG_4.

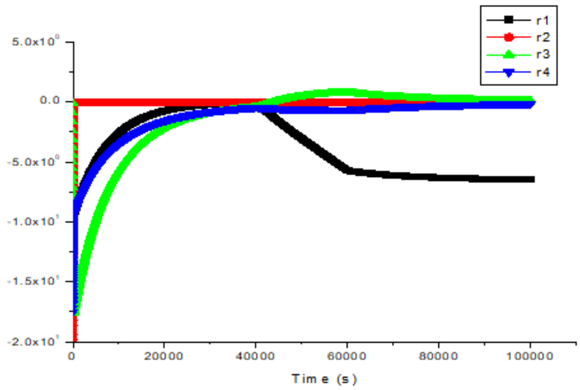


Fig. 13: Evolution of the residues with fault in the exchanger

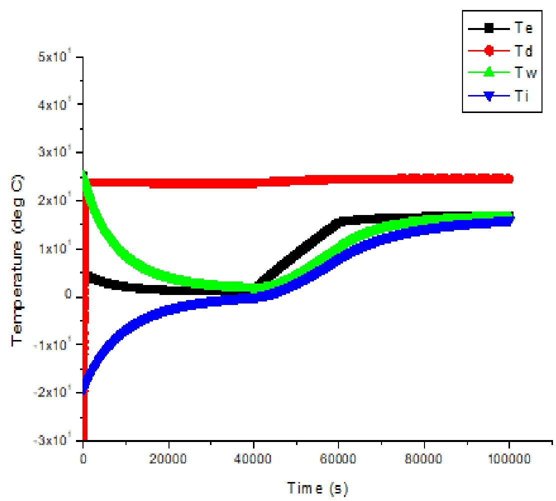


Fig. 14: Evolution of the temperatures with fault in the exchanger

Alarm 02: This fault corresponding to a fault (leakage) at the door of the industrial refrigerator modeled by the element *Cd*, this fault causes a decrease in the amount of cooling potential (figure 16). These phenomena are readable on the graph-hop model and can be quantified by the equations. This element exists in the equation of the residue r_2 for each operating mode MBG_1, MBG_2 and MBG_3 (figure 15), from which only the residue r2 is sensitive to this defect in accordance with the table 3 of signature of the defects (this defect is localized by this residue r_2). However, if this component is defective all modes of operation are affected. Therefore, switching to other operating modes is not allowed because this element exists in the operation mode without chilled water and in the operating mode without water tank, in this case the available mode is the stop mode MBG_4.

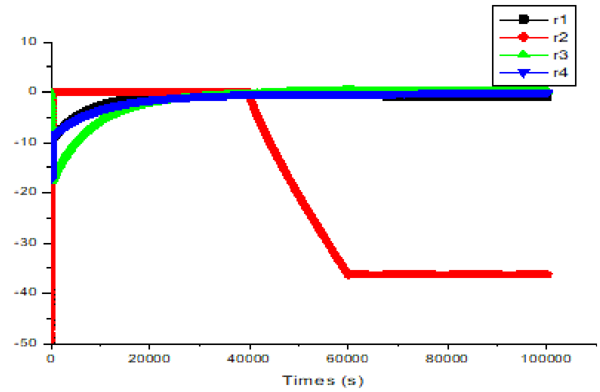


Fig. 15: Evolution of the residues with fault in the door

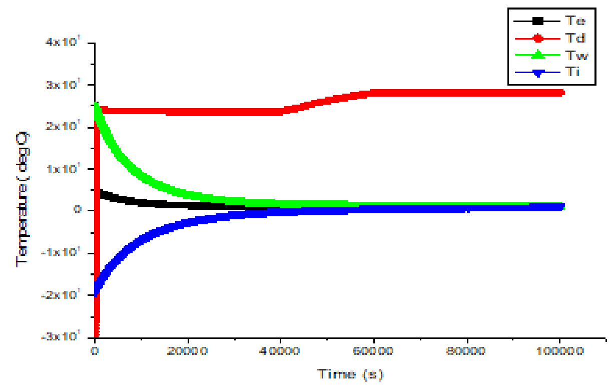


Fig. 16: Evolution of the temperature with fault in the door

Alarm 03: This fault corresponding to a fault (leakage) in the ice water of the industrial refrigerator modeled by the element Ci, this fault causes a decrease in the amount of cooling potential (figure 18). These phenomena are readable on the bond graph model and can be quantified by the equations. This element exists in the equation of the residue r_4 for the operating mode MBG_1 (figure 17), from which only the residue r4 is sensitive to this defect in accordance with the table 3 of signature of the defects (this defect is localized by this residue r_4). However, if this component is defective this operating mode will be affected. Therefore, the transition to other modes of operation is allowed eg MBG_2, MBG_3 or MBG_4.

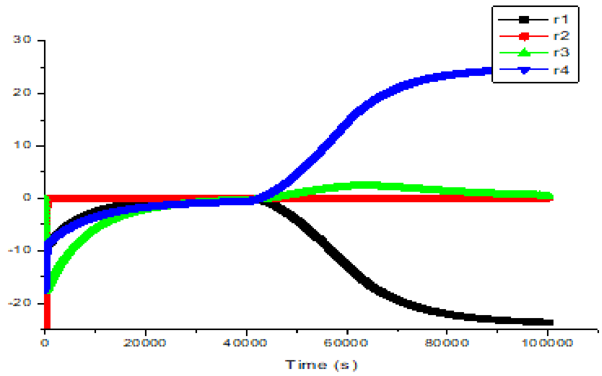


Fig. 17: Evolution of the residues with fault in the ice water

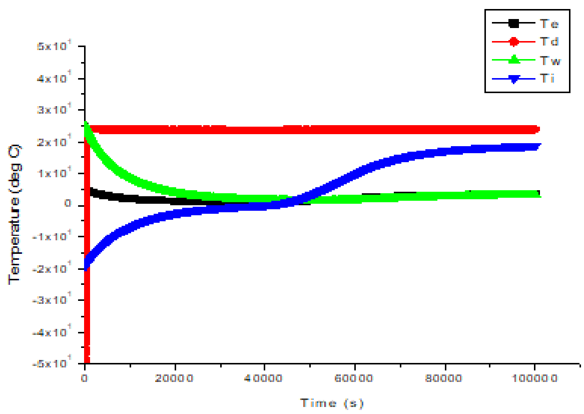


Fig. 18: Evolution of the temperature with fault in the ice water

Alarm 04: This fault corresponding to a fault (leakage) at the water of the industrial refrigerator modeled by the element *Cw*, this defect causes a decrease in the amount of cooling potential (figure 20). These phenomena are readable on the graph-hop model and can be quantified by the equations. This element exists in the equation of the residue r_3 for the operating mode MBG_1 and MBG_2 (figure 19), from which only the residue r_3 is sensitive to this defect in accordance with the table 3 of signature of the defects (this defect is localized by this residue r_3). However, if this component is defective these modes of operation will be affected. Therefore, the transition to other modes of operation is allowed eg MBG_3 or MBG_4. If the normal operating mode is the current mode, in the event of a fault, it is necessary to take into account the automatic changeover to another mode. In this case, we find that the two available modes are MBG_2, MBG_3 or MBG_4.

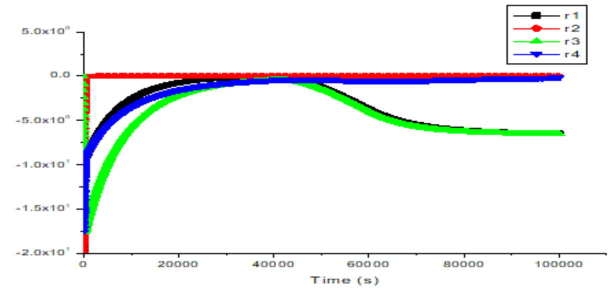


Fig. 19: Evolution of the residues with fault in the water

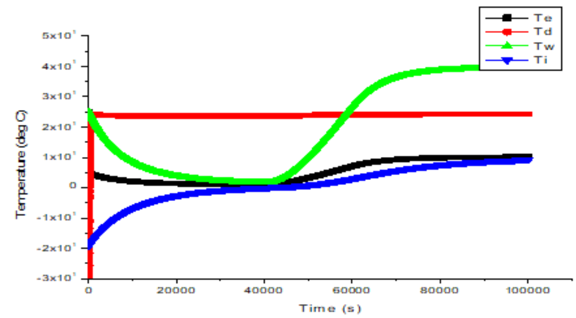


Fig. 20: Evolution of the temperature with fault in the water

c) Transfer Function Modeling Treatment

From the bond graph model MBG_1 industrial refrigerator in normal operation (figure 8), we can construct the block diagram of the below shown with duplicate links system (effort and flow) figure 21.

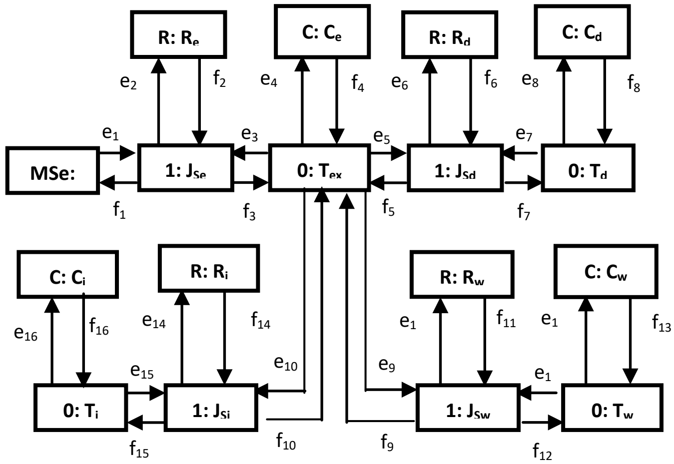


Fig. 21: Functional diagram of the industrial refrigerator with duplication of the link (effort and flow) in normal operation

The transfer function of the industrial refrigerator in normal operation H_1 (s) is the outlet temperature Tex (s) with respect to the inlet temperature Te (s):

$$H_1(s) = \frac{0.05283s^3 + 0.001319s^2}{s^4 + 0.08506s^3 + 0.001504s^2} \quad (5)$$

From the bond graph model MBG_2 industrial refrigerator in operation without iced water (figure 9), we can construct the block diagram of the below shown with duplicate links system (effort and flow) figure 24.

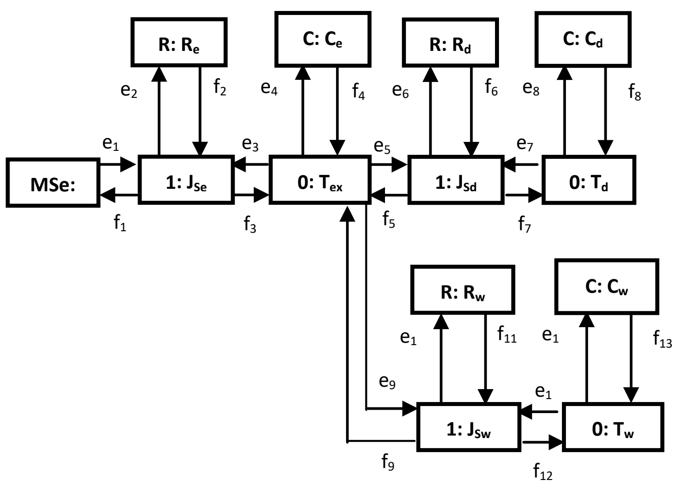


Fig. 22: Functional diagram of the industrial refrigerator with duplication of the link (effort and flow) in operation without iced water

The transfer function of the industrial refrigerator without iced water H_2 (s) is the outlet temperature Tex (s) with respect to the inlet temperature Te (s):

$$H_2(s) = \frac{0.05283s^2}{s^3 + 0.06014s^2} \quad (6)$$

From the bond graph model MBG_3 industrial refrigerator in operation without iced water (figure 10), we can construct the block diagram of the below shown with duplicate links system (effort and flow) figure 23:

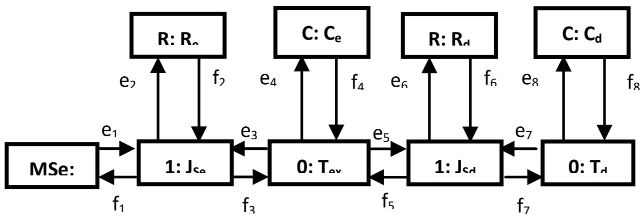


Fig. 23: Functional diagram of the industrial refrigerator with duplication of the link (effort and flow) in operation without water

The transfer function of the industrial refrigerator without water H_3 (s) is the outlet temperature Tex (s) with respect to the inlet temperature Te (s):

$$H_3(s) = \frac{0.05283s}{s^2 + 0.05682s} \quad (7)$$

Figure 24 shows the evaluation of the transfer function for the three modes of operation (normal operating mode, reduced operating mode and stop mode).

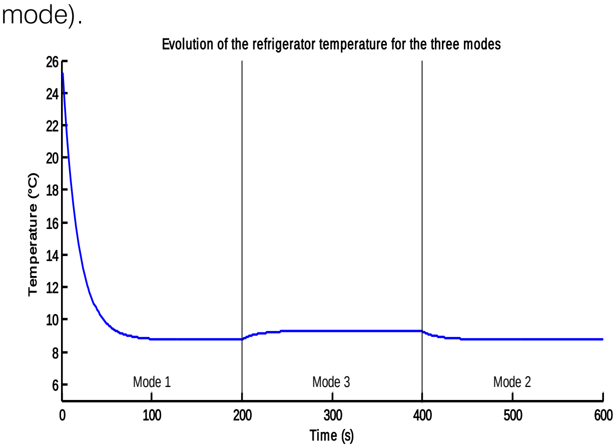


Fig. 24: Evaluate the transfer function for each mode

d) Control of the Temperature in Three Modes

In this part, we propose the control of the refrigerator's temperature for the three modes by the design of a PI controller for each mode. In fact the recursive equation of this controller is:

$$u(k) = u(k-1) + (K_p + K_I T_s)e(k) - K_p e(k-1) \quad (8)$$

Then, we will consider the recursive equation for each model. So by fixing a sampling time *Ts=1s* and a first holder folder we obtained the following recursive equations for the three models:

$$y_1(k) = 1.496y_1(k-1) - 0.5513y_1(k-2) + 0.1615u_1(k-1) + 0.004792u_1(k-2) - 0.1179u_1(k-3) \quad (9)$$

$$y_2(k) = 0.9416y_2(k-1) + 0.02589u_2(k-1) + 0.02538u_2(k-2) \quad (10)$$

$$y_3(k) = 0.9448y_3(k-1) + 0.02592u_3(k-1) + 0.02544u_3(k-2) \quad (11)$$

The determination of the K_p and K_i parameters leads to the following control laws:

$$u_1(k) = u_1(k-1) + 6.41e(k) - 6.21e(k-1) \quad (12)$$

$$u_2(k) = u_2(k-1) + 6.495e(k) - 6.3e(k-1) \quad (13)$$

$$u_3(k) = u_3(k-1) + 6.3e(k) - 6.1e(k-1) \quad (14)$$

By implementing these control laws, we obtained the evolution of the temperature of the refrigerator for the three modes.

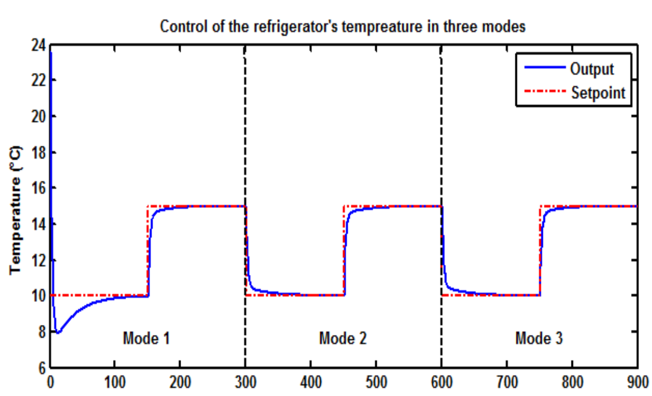


Fig. 25: Control of the industrial refrigerator's temperature for three modes

From Figure 25, it is noted that the designed PI controllers allow the regulation of the temperature in spite of the variation of the set-point and the switching between modes.

IV. Conclusions

In this article we used three models to determine the supervision of an industrial system. Indeed the external model provides a functional description for an industrial system; this task is insufficient to supervise the behavior of all elements of the system. To complete the inadequacy of this task, we have introduced another model called bond graph. The bond graph model is a tool based on a physical knowledge of the industrial system; this model bond graph models the industrial system element by element. This modeling, which clearly represents the physical phenomena of the industrial system, improves the surveillance system and the security (fault detection and localization). The use of the model of the transfer function by the bond graph model allowed us to see the ready for each mode of operation (normal operating mode, reduced operating mode and stop mode), also the model of the function transfer allowed us to see the swing of the industrial system for these modes. By considering these representations, we designed PI controllers in order to regulate the temperature for each mode.

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The Steel Industry of Brazil and Argentina. From its Creation to its Privatization

By Roberto Dante Flores
Universidad de Buenos Aires

Abstract- The objective of this work will be to compare the impact of the development of the state steel industry in Brazil and Argentina, analyzing multiple aspects from politics, economics and society. To carry out the work, the Minutes and Reports of the companies and research prepared by different authors, knowledgeable about the steel industry in Brazil and Argentina, were used. First, we consider the international political and economic context that prompted the governments of Brazil and Argentina to develop their own steel industry. Then, we observe the beginning of the large steel companies and their population impact on the small cities where they were installed. Finally, we studied the privatizations of these companies and drew some comparative conclusions between the Brazilian steel system and the Argentine steel plan.

Keywords: brazil, argentine, steel industry, population impact, privatizations.

GJRE-G Classification: DDC Code: 338.47669142097488 LCC Code: HD9517.M85

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La industria siderúrgica de Brasil y Argentina. Desde su creación hasta su privatización

Roberto Dante Flores[2]

Abstract- The objective of this work will be to compare the impact of the development of the state steel industry in Brazil and Argentina, analyzing multiple aspects from politics, economics and society. To carry out the work, the Minutes and Reports of the companies and research prepared by different authors, knowledgeable about the steel industry in Brazil and Argentina, were used. First, we consider the international political and economic context that prompted the governments of Brazil and Argentina to develop their own steel industry. Then, we observe the beginning of the large steel companies and their population impact on the small cities where they were installed. Finally, we studied the privatizations of these companies and drew some comparative conclusions between the Brazilian steel system and the Argentine steel plan.

Keywords: brazil, argentine, steel industry, population impact, privatizations.

Resumen- El objetivo de este trabajo será comparar el impacto que tuvo el desarrollo de la industria siderúrgica estatal en Brasil y Argentina, analizando múltiples aspectos: políticos, económicos y sociales. Para realizarlo se recurrió a las Actas y Memorias de las empresas y a investigaciones elaboradas por distintos autores, conocedores del ámbito siderúrgico en Brasil y Argentina. En primer lugar, se considera el contexto político y económico internacional que impulsó a los gobiernos de Brasil y Argentina a desarrollar su propia industria siderúrgica. Luego, se observa el inicio de las grandes empresas siderúrgicas y su impacto poblacional en las pequeñas ciudades donde fueron instaladas. Por último, estudiamos las privatizaciones de esas empresas y sacamos algunas conclusiones comparativas entre el sistema siderúrgico brasileño y el plan siderúrgico argentino.

Palabras Clave: brasil, argentina, industria siderúrgica, impacto poblacional, privatizaciones.

I. Introduccion

Distintos autores han abordado los comienzos y el desarrollo de la industria siderúrgica en Brasil y Argentina. Moniz Bandeira (2004, 2007) muestra el contexto internacional durante la Segunda Guerra Mundial y sus vínculos con la industria del acero. En ese conflicto, considera que la sobreactuada posición neutralista del presidente Getulio Vargas ante los Estados Unidos (EE.UU) fue un factor decisivo para obtener el financiamiento de la primera planta siderúrgica brasileña. Henrich (2010) profundiza la relación de la política exterior en un escenario de guerra mundial, y la implantación de la industria del acero en Brasil. Por su parte, los militares argentinos, contrariamente a sus pares brasileños que estrecharon vínculos con EE.UU., estuvieron forzados a buscar soluciones autónomas en materia de defensa (Rapoport, 1992).

Dinius (2010) realiza una mirada sociológica de las relaciones industriales y laborales de la brasileña Companhia Siderurgica Nacional (CSN), desde sus inicios en la década de 1940. Su investigación posibilita analizar el rol que desempeñaron los trabajadores del acero –bajo las políticas de sustitución de importaciones– en el desarrollo social y económico de Brasil. También veremos la consolidación económica de la Companhia como productor de acero. Políticamente, símbolo del varguismo, y simbólicamente, hito de la industrialización brasileña. En otra investigación, destaca la construcción de la CSN como ciudad empresa (*company town*) y su intento por establecer un nuevo modelo para el desarrollo económico y social del país. Una política de bienestar del estado varguista, con programas de asistencia y mecanismos de ordenamiento social. (Dinius 2013).

Las sucesivas etapas de expansión de la CSN, durante 30 años, son estudiadas por Moreira (2000). El proyecto original (Plan A) dio lugar, entre 1951 y 1955, a las obras de ampliación del nuevo alto horno (Plan B). Para continuar contratando equipos y servicios importados, mediante el otorgamiento de crédito estadounidense (Plan C). Boto (2012) también realiza un estudio por etapas de la industria siderúrgica, pero en Argentina. La autora señala el proceso de instalación y desarrollo de la empresa Altos Hornos Zapla (AHZ), y el rol del Estado nacional en la industrialización por sustitución de importaciones. Sobre la construcción planificada del espacio físico, la infraestructura y la

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formación de un mercado de trabajo en AHZ, expone Castillo (2007, 2012). Para obtener algunas estadísticas poblacionales, y comprender cómo se implementó el primer centro siderúrgico integral de la Argentina, es necesaria la compilación de Bergesio y Golovanevsky (2016).

El inicio de la corriente privatizadora mundial y su alcance en la industria del acero en Brasil y Argentina es analizado por Aspiazu, Basualdo y Kulfas (2005). Ese trabajo permite confrontar con los datos proporcionados por Mendes de Paula (1997) para las privatizaciones de la industria siderúrgica en Brasil. También Amarante de Andrade (1994, 2001) aporta datos para comprender el contexto creciente de internacionalización del acero y el período de pos privatización. En Argentina profundas transformaciones económicas y sociales ocurrieron en Palpalá y San Nicolás. Esta última ciudad fue escenario del proceso de reestructuración y privatización de la Sociedad Mixta Siderurgia Argentina (SOMISA), el mayor establecimiento productor de acero nacional. Este proceso se realizó según las recomendaciones de consultoras internacionales (Rofman y Peñalva, 1995).

El presente artículo se divide en cuatro partes que abordan: 1) el contexto político y económico internacional, 2) las características del desarrollo de la CSN en Brasil y del Plan Siderúrgico Argentino (PSA), con sus aspectos de ciudad empresa, *company town*, 3) el momento de las privatizaciones de las empresas, y por último 4) algunas conclusiones comparativas entre el sistema siderúrgico estatal brasileño y el PSA.

II. Contexto Internacional. Sustitución a las Importaciones de Acero

En las primeras décadas del siglo XX, Argentina y Brasil participaron activamente en el proceso de industrialización. Su objetivo fue profundizar la primera etapa de sustitución de importaciones mediante la incorporación de industrias básicas, dentro de las cuales la producción siderúrgica asumía una importancia central. A continuación se mostrará cómo fue ese proceso en ambos países y la influencia del contexto internacional.

Brasil, aunque rico en yacimientos de hierro, poseía un sector productor de hierro y acero de muy poca relevancia. Pero en 1910 ganó terreno el debate sobre el problema nacional del acero. Y surgieron algunos proyectos que vincularon la producción de acero con los proyectos para la exportación de hierro de Minas Gerais. Durante la Primera Guerra las dificultades de oferta que enfrentó la economía brasileña acentuó la comprensión del problema por parte de los gobernantes y también de los empresarios. Durante 1920 el gobierno de Brasil suscribió un contrato con Itabira Iron Ore Company, empresa inglesa con participación de capitales norteamericanos. La empresa se comprometía a construir una planta siderúrgica, a cambio del monopolio del transporte del mineral. Después de ocho años en el Congreso, en 1928 fue legalizado el contrato con Itabira. Pero en 1931 el presidente Getulio Vargas (gobernó Brasil de 1930 a 1945, y de 1951 a 1954), decretó la caducidad del contrato y anunció la constitución de la Companhia Siderúrgica Nacional (CSN). Con la instalación del *Estado Novo* (1937) la planta se transformó en una prioridad gubernamental, y una carta de negociación en las relaciones entre Brasil y dos potencias rivales, Estados Unidos y Alemania.

El presidente de los EE.UU., Franklin Roosevelt, por razones geopolíticas estaba interesado en alinear a su país con Brasil. En 1939 se entablaron conversaciones con la empresa estadounidense United Steel para su participación en el programa siderúrgico brasileño, pero las expectativas se vieron frustradas. Esto indica que no había mucho interés por parte de las empresas estadounidenses en el desarrollo de la industria siderúrgica brasileña. El 11 de junio de 1940, tres días antes de la caída de París por las tropas alemanas de Adolf Hitler, Vargas, a bordo del acorazado *Minas Gerais* pronunció un discurso nacionalista y socializante, donde distanció a Brasil de los Estados Unidos. Este discurso fue percibido como "germanófilo" y dirigido al presidente de los EE.UU., como amenaza de alineamiento de Brasil con las potencias del Eje (Alemania, Italia, Japón).

El discurso nacionalista de Vargas evidencia que Brasil todavía aspiraba a una cierta neutralidad, semejante a la Argentina. Los Estados Unidos necesitaban la cooperación efectiva de Brasil, dada la importancia de su posición estratégica en América del Sur. Pero, si la empresa alemana Krupp invertía en la industria siderúrgica brasileña, fortalecería a los sectores pro-alemanes de las Fuerzas Armadas del gobierno de Vargas. Los nacionalistas brasileños no estaban dispuestos a conceder fácilmente la instalación de bases estadounidenses en las costas de Brasil. Pero posibilitaron la negociación con los EE.UU.: dinero a cambio de usar sus bases militares.

Rápidamente, en enero de 1941, se aprobó la construcción de todo el plan siderúrgico brasileño. Es un hecho que la posición política internacional del presidente de Brasil facilitó la liberación de fondos estadounidenses. Y así abrió las negociaciones para un mutuo entendimiento a largo plazo. En abril de 1941, la CSN se constituyó empresa de capital mixto (inaugurada en 1946, durante la presidencia del general Eurico Dutra). Finalizado el mes de agosto de 1941, el gobierno estadounidense aseguró un crédito de 20 millones de dólares para que la CSN construyese en Volta Redonda (Estado de Río de Janeiro) el mayor complejo siderúrgico de América Latina. Así se asentaron los cimientos de la industrialización y el complejo militar-industrial de Brasil.

El mismo mes del anunciado crédito, Brasil autorizó a los EE.UU. a realizar operaciones militares utilizando las bases en el territorio brasileño. Y poco antes de que EE.UU entrase en la guerra, se realizaron negociaciones en Washington para defender el continente americano ante cualquier agresión de los países del Eje. El posterior ingreso de los Estados Unidos en la arena bélica mundial intensificó este proceso de alineación, con el envío de equipo militar y bienes de capital. De este modo se consolidaba un plan a largo plazo: la prominencia de los EE. UU. en América Latina y de Brasil en América del Sur.

Al mismo tiempo, pero en sentido contrario, Argentina comenzó a sufrir un proceso de deterioro en las relaciones con la potencia norteamericana. Fue a partir de la declaración de guerra de los EE.UU a Japón, el 8 de diciembre de 1941. La continuidad del neutralismo argentino implicó la sanción del país, dejándolo fuera de la ley de Préstamos y Arriendos, que imposibilitaba comprar armas en los EE.UU. Otra medida, alentada por el secretario de Estado, Cordell Hull, fue implementar un sistema de controles de las exportaciones hacia la Argentina, a través del Board of Economic Warfare.

El mismo año que los EE.UU. ingresaron en la guerra, Argentina dio origen a la Dirección General de Fabricaciones Militares (DGFM). Esta entidad autárquica, dependiente del Ministerio de Guerra y dirigida por el general Manuel Savio, tenía por finalidad principal la fabricación de materiales de guerra. Pero un aspecto no menos importante era organizar el país para su defensa en el aspecto industrial. Y para ello fue prioritario realizar un plan de exploraciones y explotaciones tendientes a la obtención de minerales –entre ellos el hierro– para la industrialización de elementos bélicos.

La DGFM tuvo a su disposición considerable cantidad de dinero durante la guerra. Esta se incrementó en 1943. El incremento del presupuesto esos años se fundamentó en la necesidad de la DGFM de encarar “importantes planes de trabajo encomendados” y la construcción de fábricas y plantas industriales. Las dificultades de la guerra le permitieron al Estado nacional legislar para aumentar la capacidad de producción en bienes sensibles a la Defensa. No obstante los recursos financieros disponibles, las carestías eran de abastecimiento (los países europeos en guerra) y, particularmente, políticas (el Departamento de Estado de los EE.UU.).

Esta situación tuvo un giro cuando el secretario de Estado Cordell Hull fue reemplazado por Edward Stettinius Jr. A fines 1944 lo acompañó Nelson Rockefeller, secretario adjunto de Asuntos Latinoamericanos, y ambos llevaron adelante una política de acercamiento a la Argentina. Los frutos de esta buena relación se vieron con la declaración argentina de guerra a los países del Eje (27/3/1945) y su consecuente ingreso a las Naciones Unidas. A partir de entonces Washington liberó las restricciones al comercio con Argentina.

Pero, en abril de 1945, cuando EE.UU. abandonaba la política de exportaciones restrictiva hacia la Argentina, falleció el presidente Roosevelt.[3] Entonces designaron embajador en Buenos Aires al político y empresario Spruille Braden, acérrimo opositor al vicepresidente argentino Juan D. Perón. En el cargo duró poco –de mayo a agosto de 1945– no obstante Braden quiso que las “licencias de exportaciones” estuvieran condicionadas a las recomendaciones de su Embajada. Al poco tiempo Braden fue designado secretario adjunto de Asuntos Latinoamericanos. Un estratégico puesto con el que continuó, con mayor poder, su tarea contraria al abastecimiento industrial argentino.

III. Transformación de Volta Redonda por CSN

A inicios de la década de 1940 Volta Redonda era una pequeña localidad, estación de ferrocarril entre Rio de Janeiro y San Pablo. Contaba con una población cercana a las 10.000 personas, quienes vivían de las lecherías y plantaciones de cítricos. La decisión de construir una *company town*[4] respondió en parte a la necesidad de alojar mano de obra y mejorar la actividad económica de un pueblo pequeño.

El plan inicial consideraba albergar 4.625 trabajadores y sus familias. La construcción comenzó a mediados de 1942. Hacia 1946, la CSN había terminado 72 viviendas para ingenieros y altos administrativos, 500 habitaciones para empleados de oficina, 1.878 para trabajadores del taller y 2 hoteles que podían hospedar a 120 empleados solteros.

El diseño urbano combinaba el bienestar social con el respeto a la autoridad. Las características y la ubicación de las casas reflejaban las jerarquías dentro de la CSN. Los administradores e ingenieros ocupaban amplias villas en la zona del *Laranjal*, una ladera con brizas permanentes, ideal para el verano. Su ubicación elevada reforzaba el rol de los ingenieros como líderes ejemplares que los trabajadores debían respetar. Las visitas importantes se hospedaban en *Hotel Bela Vista*, con vista al pueblo y a la fábrica. Los técnicos y trabajadores calificados vivían en la *Vila Santa Cecília*, el corazón de la *company town*, cerca de la entrada principal a la planta. Sus calles contaban con viviendas

[3] “En las futuras decisiones de asignaciones y licencias, la Argentina debe ser tratada en igualdad de condiciones que las otras repúblicas”. Washington, April 12, 1945, 835.24/4-1245, *Foreign relations of the United States (FRUS), diplomatic papers, 1945. The American Republics*, Volume IX, 1945, p. 530.

[4] Una comunidad (barrio o pequeña localidad) dependiente de una gran empresa para la mayoría de sus servicios (empleo, vivienda, actividad comercial). *Merriam-Webster Dictionary*, Massachusetts, 1991, p. 267.

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familiares de ladrillos, con todas las comodidades urbanas y jardines. Los empleados solteros también vivían en *Vila Santa Cecília*, en los *hotéis dos solteiros*, que alojaban a centenas de funcionarios. Las viviendas familiares para trabajadores no calificados estaban hechas de madera, eran menos espaciosas pero contaban con agua potable, alcantarillado y electricidad. Ubicadas en las laderas alrededor de la fábrica, estaban expuestas a los ruidos y olores de la permanente producción de acero. El *Bairro Rústico* fue el primer barrio obrero.

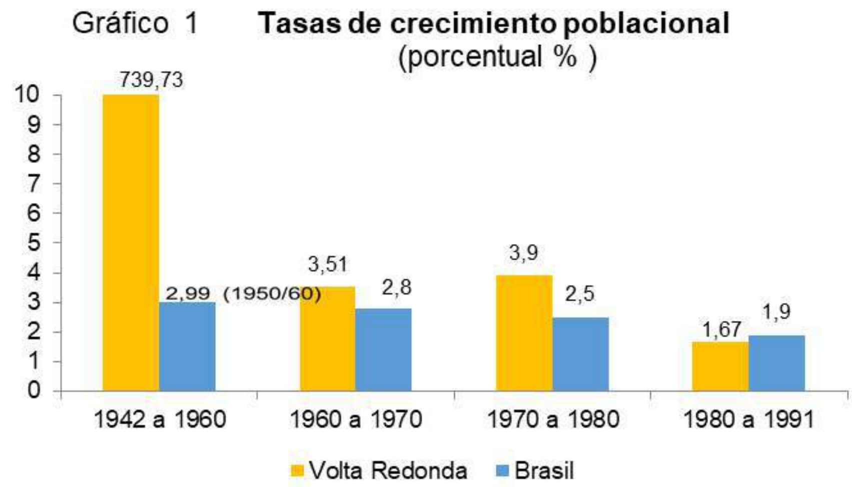
El diseño de la *Vila Santa Cecília* también reflejaba la visión que el *Estado Novo* tenía del Brasil industrial. La calle principal, *Rua* 33, comenzaba en la fábrica y cruzaba el centro comercial y las calles residenciales, culminando en una gran plaza pública donde se ubicaba la escuela técnica. En el diseño de las áreas residenciales, se destacaban la limpieza, paz y tranquilidad, lo cual contrastaba intencionalmente con la fábrica y su desorden, peligro y bullicio. El tráfico de automóviles estaba restringido a las arterias centrales y las calles residenciales de adoquines de piedra eran para uso exclusivo de peatones y bicicletas. Este diseño evocaba la ciudad jardín del siglo XIX con sus calles residenciales arboleadas, jardines cuidadosamente mantenidos y sus espacios abiertos para parques. La Compañía incluso consideró reforestar las laderas alrededor del pueblo. En el trazado de *Vila Santa Cecília* destacaban los edificios públicos, el hospital, la escuela técnica y la iglesia católica. El centro de la *company town* era una expresión urbanística del *Estado Novo* y la modernización industrial de Brasil. Allí confluían el trabajo industrial, la educación técnica, la salud pública, y la paz social.

Ese orden social estaba sustentado económicamente, los trabajadores tenían alquileres subsidiados y acceso a los servicios urbanos. El costo mensual de una casa –dos habitaciones y sin cuartos para personal de servicio doméstico– era equivalente al 25 por ciento del sueldo promedio de un trabajador semi o no calificado. Las casas más lujosas –tres habitaciones y dependencias para el personal de servicio doméstico– tenían un alquiler accesible, pudiendo ser alquiladas por técnicos y trabajadores calificados. La CSN también operaba los servicios de agua, alcantarillado y distribuía electricidad desde una planta hidroeléctrica cercana Sólo cobraba los gastos de operación y los descontaba directamente del salario del trabajador. Hacia 1946, la Compañía mantenía un hospital, puestos de salud, dos escuelas primarias, una escuela secundaria, almacenes donde se vendían alimentos a precios subsidiados, varios parques y canchas deportivas para las actividades recreativas.

En la década de 1960 Volta Redonda abandonó oficialmente la condición de ciudad empresa. CSN, y otras empresas estatales brasileñas, pasó a regirse por criterios de eficiencia, idénticos a los del sector privado, organizándose en forma de conglomerados, maximizando beneficios y ejerciendo actividades internacionales. Cambios que se vieron necesarios para garantizar la viabilidad de una empresa que había gastado muchos recursos para garantizar la reproducción de su fuerza de trabajo. ¿Qué había ocurrido para que ocurriese este giro? Los cambios se explican por las enormes pérdidas que la empresa estaba sufriendo por la falta de competitividad en el mercado siderúrgico.

El elevado número de puestos de trabajo y la extensión de su política de previsión social fueron los datos que contribuyeron al giro estructural de la Compañía. La volatilidad de la actividad siderúrgica debido a las inestabilidades del mercado internacional generó frecuentes oleadas de despidos en la planta. En 1983 las dificultades enfrentadas por la Compañía –agravadas por una crisis siderúrgica global– llevaron al despido de 5.000 empleados. [5] Esto trajo como consecuencia el mismo resultado en las pequeñas y medianas industrias proveedoras de piezas de mantenimiento para la planta. Por la retracción de la demanda de productos siderúrgicos, estas empresas también despidieron a sus trabajadores. Entonces, el número de desempleados en Volta Redonda trepó a 8.000 (sobre un total aproximado de 40.000 empleos directos e indirectos). De este modo disminuyó el crecimiento en la población de Volta Redonda, por primera vez inferior al de Brasil (ver Gráfico 1).

[5] A nivel mundial, las tasas de crecimiento en la producción de acero cayeron de 1,87 % (1970/80) a 0,72% (1980 /90). En Brasil, las inversiones siderúrgicas, entre 1982 y 1984, cayeron de 2.224 a 509 millones de dólares. Aspiazu, Basualdo y Kulfas, pp. 3 y 166.



FUENTE: Elab. propia. Datos de Gomes Landes, Marques de Castro, Diario Oficial (DOU) y Anuarios Estadísticos de Brasil.

En resumen, al inicio de la década de 1940, esa tranquila localidad entre Rio de Janeiro y San Pablo siguió los derroteros del proyectado *Estado Novo* industrial. De la lechería y los cítricos saltó hasta convertirse en la "ciudad del acero". Para 1946 CSN ya había terminado de construir alojamientos para 2.841 trabajadores. En 1950 las viviendas de la empresa alojaban a 35.000 trabajadores y el pueblo –por ese impulso industrial– alcanzó los 50.000 habitantes. En 1989 CSN generaba alrededor de 25.000 empleos directos en Volta Redonda, y gestionaba un complejo sistema de bienestar social que incluía escuelas, clubes y un hospital para empleados y sus familias. Estos activos de la empresa fueron incluidos en la subasta de privatización, realizada en abril de 1993, en la Bolsa de Valores de Río de Janeiro.[6]

IV. Palpalá y Altos Hornos Zapla (AHZ)

Al finalizar la década de 1930, en las serranías de Zapla, próximas a la capital de Jujuy, Argentina, fue descubierto un yacimiento de hierro. Poco después, en 1942, se aprobó un convenio entre la provincia y la DGFM, con el fin de la explotación del mineral de hierro y su procesamiento siderúrgico. Al inicio de 1943, el establecimiento industrial creado recibía el nombre de Altos Hornos Zapla (AHZ). Y alrededor del mismo comenzó a formarse un pueblo, llamado Palpalá.

La ubicación del Centro Siderúrgico en Palpalá se debió a consideraciones estratégicas. Relativamente cerca de los dos yacimientos de hierro (a 12 y 37 kilómetros) y a 5 kilómetros del Centro Forestal proveedor del carbón vegetal (proveniente de bosques de eucaliptus) que alimentaba los altos hornos. Además, a 500 metros del Río Grande, proveedor del agua necesaria, y a escasos metros del Ferrocarril General Belgrano. Palpalá, al iniciar la década de 1940, era un pequeño pueblo rural con escasas 400 personas, Esa región tradicionalmente estaba constituida por fincas destinadas al pastoreo y a la agricultura. Su vida era animada por el paso diario del ferrocarril proveniente de Buenos Aires con destino a Yacuiba, Bolivia.

El esquema productivo de AHZ se basó en el Plan Siderúrgico Argentino (PSA) inspirado por el general Manuel Savio, sancionado como ley nacional 12.987 en 1947. En pocos años el esquema articuló cuatro centros productivos: Mina 9 de octubre, Centro siderúrgico Palpalá, Centro Forestal y Centro Mina Puesto Viejo. Estos centros a su vez tenían población y localidad urbanizada. El objetivo era afianzar la industria siderúrgica argentina completando el ciclo productivo desde la extracción del hierro hasta la elaboración de laminados de acero. Este sistema se denominó "fábrica integrada".

La primera colada de arrabio se realizó el 11 de octubre de 1945, utilizando un único horno con carbón vegetal. Esa actividad fue el inicio de un cambio en la vida de la zona. Con el aporte técnico de la empresa Svenska –de un país neutral en la guerra, Suecia– se pudo comenzar a suplir el faltante de arrabio para la industria siderúrgica nacional. Hasta ese momento las plantas productoras de acero en Argentina utilizaban chatarra nacional e importada. Y la capacidad de laminación era satisfecha con una gran proporción de palanquillas importadas (la industria siderúrgica existente dependía en un 70% de materias primas importadas).

El proceso de mejoras en AHZ fue paulatino. Seis años después, 1951, con la inauguración del segundo alto horno se fue completando la primera etapa de la producción de arrabio. Entonces el coronel

[6] Lima, p. 50. En 1994 CSN, bajo el control del sector privado, produjo por primera vez 4,6 millones de toneladas. Objetivo que perseguía la compañía desde los años ochenta. http://www.fgv.br/cpdoc/acervo/dicionarios/verbete-tematico/companhia-siderurgica-nacional

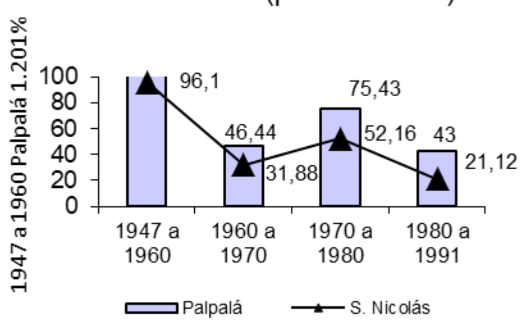
Armando Martijena elaboró un informe técnico (1957) para ampliar el ciclo del arrabio y producir acero. Así, en 1959, entró en funcionamiento el tercer alto horno, iniciándose la etapa dirigida a la futura producción de acero. El cuarto alto horno se inauguró en 1964. Entonces la modernización de la fábrica permitió alcanzar la capacidad de producción diaria de 125 toneladas de arrabio. El año 1964 fue clave, ya que también comenzaron a operar las plantas de acero (Thomas y Eléctrico) y de laminación (Blooming). De este modo pudo cumplirse el objetivo planificado por Martijena: una industria integrada con productos de acero laminados para el consumo.[7]

A partir de las mejoras tecnológicas de los años ´60 se dio, simultáneamente, una mejora sustancial en la infraestructura y en las condiciones sociales de Palpalá. En 1964 AHZ –en los cuatro centros de producción– proporcionó habitación para algo menos del 50% de sus empleados: 491 familias y 794 trabajadores solteros. En la mina, denominada "9 de octubre", trabajaban 410 obreros y vivían 1200 personas, en viviendas instaladas por la DGFM.[8] Para 1970 las nuevas plantas de acero de AHZ producían el 7,18% de la producción nacional. En 1976 comenzó a funcionar el quinto horno (capacidad de 250 toneladas de producción diaria de arrabio) y generó una transformación del proceso siderúrgico que se manifestó en el incremento de la producción, tanto del arrabio como de los diferentes tipos de acero.

En 1980 AHZ, en sus cuatro centros, contaba con un total de 495 viviendas: 123 para profesionales, 155 para sub profesionales y 217 para empleados y obreros. También poseía una vasta red de servicios educativos y hospitalarios. Al aproximarse sus cuarenta años la empresa estatal había fomentado no sólo la minería, la industria siderúrgica y del carbón vegetal, sino también numerosas industrias subsidiarias. Esta actividad modificó sustancialmente el perfil productivo y social agropecuario tradicional de la zona.

Pero, luego de más de cuarenta años de expansión, la localidad ingresó en una instancia regresiva. Declinaron los planes de producción con reducción de las extracciones de mineral. En 1990 terminó la explotación de la Mina 9 de octubre. Finalmente la privatización de la empresa acentuó los despidos que –a semejanza de Volta Redonda– impactaron en el crecimiento de la ciudad cercana, Palpalá. Esta caída (32%) fue todavía superior al decrecimiento intercensal de la ciudad siderúrgica San Nicolás.

Gráfico 2 **Tasas de crecimiento intercensal** (porcentual %)



FUENTE: Elaboración propia con datos del Instituto Nacional de Estadística y Censos (INDEC).

En el Gráfico 2 se observa un crecimiento intercensal similar entre ambas localidades siderúrgicas. La excepción está en el aumento descomunal de la población en Palpalá (1.201%, correspondiente al intervalo 1947/1960). Dicho crecimiento era consecuencia de la mayor atracción relativa de mano de obra que produjo, en poco tiempo, la instalación de una gran planta siderúrgica en una pequeña localidad rural. En las dos ciudades siderúrgicas las tasas superaron ampliamente al crecimiento poblacional de la República Argentina (ver Cuadro 1).

[7] En Argentina las únicas empresas siderúrgicas integradas (alto horno, acería y laminación) pertenecían a la DGFM (AHZ y SOMISA). Recién a partir de 1980 lograron integrar el proceso las privadas Acindar y Siderca. Ver Aspiazu, Basualdo y Kulfas, p. 25.

[8] La denominación "viviendas" (o "pabellones departamentos") es utilizada para los empleados casados y "pabellones" para los solteros. Bergesio, y Golovanevsky, 2016, pp. 49-50.

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Cuadro 1 Tasas de crecimiento poblacional (%)

Período	Palpalá	San Nicolás	Argentina
1947 a 1960	1201	96,1	25,9
1960 a 1970	46,44	31,88	16,7
1970 a 1980	75,43	52,16	19,7
1980 a 1991	43	21,12	16,7

FUENTE: Elaboración propia. Datos del INDEC

V. San Nicolás y la Instalación de Somisa

En 1947 el partido de San Nicolás de los Arroyos, al norte de la provincia de Buenos Aires (a 232 km de la Capital Federal) tenía 39.000 habitantes. La población potencialmente activa, en edad de trabajar, era 30.000. Hasta ese momento la localidad homónima constituía un típico lugar bonaerense, vinculado al sector agropecuario. A partir de la construcción de la planta siderúrgica de SOMISA la ciudad de San Nicolás se transformó en un polo de atracción para los trabajadores rurales. Ellos provenían principalmente del litoral norte, zona poco industrial de la Mesopotamia argentina, y se incorporaban a las empresas de construcción. También llegaron profesionales y técnicos con garantías de viviendas, que coincidían con los obreros no calificados que arribaban sin garantías de empleo.

El Barrio Residencial cercano a la planta se construyó con la finalidad de albergar a técnicos y profesionales extranjeros. Eran aquellos que contratados por las empresas, brindaban asesoramiento técnico. Los profesionales argentinos también se alojaron allí, participando de un proceso de formación y especialización en la industria siderúrgica. El barrio se organizó alrededor de una avenida que conducía a varios subconjuntos de viviendas. Sobre la avenida central se ubicaron el núcleo cívico y comercial (correo, delegación policial, cooperativa de consumo). En los años de las décadas de 1960 y 1970 se construyeron escuelas, una iglesia y un club. En 1958 se proyectaron numerosas viviendas: 24 de categoría superior, 134 de categoría intermedia y 484 de categoría inferior. En el ejercicio de SOMISA n°16, 1962/63, se menciona la existencia de 642 viviendas (12,8% del total de 5.015 trabajadores, en la planta de San Nicolás).

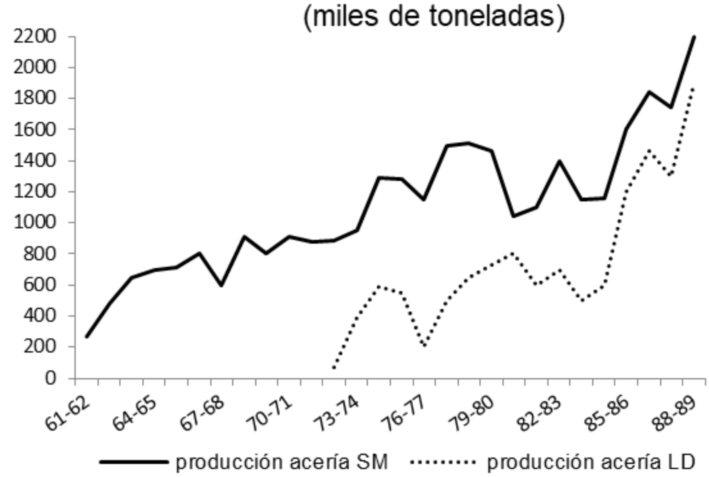
Paulatinamente comenzó a formarse un barrio, *company town*, donde trabajadores, técnicos y profesionales compartían un estrato particular del ámbito siderúrgico. Existía un proceso de atracción de mano de obra específica y calificada en un momento de instalación de industrias manufactureras de capital extranjero. Las viviendas dentro del barrio pasaron a ser un centro de atracción necesario por la cercanía con la empresa. A semejanza de las experiencias de AHZ, la instalación del barrio siguió esquemas definidos y jerarquizados. La segmentación era propia de la organización en un espacio urbano, pero también reflejaba el proceso productivo vivido en la planta. Se diferenciaba a los trabajadores y técnicos calificados del resto de los obreros. Quienes vivían en el barrio y quienes se alojaban afuera.

Esta diferenciación se originó con el arribo masivo de trabajadores quienes, atraídos por las obras, se instalaban en grandes extensiones de tierras fiscales. Así surgieron precarios barrios sin servicios: "villas misera", alrededor del casco urbano. Luego comenzó un proceso de urbanización apresurado por el capital inmobiliario, vendiéndose terrenos en lotes, sin servicios (agua potable, cloacas) ni tampoco infraestructura urbana (pavimento, alumbrado). A mediados de la década de 1960 se implementaron varios planes de vivienda del Estado provincial y municipal. Los trabajadores no calificados se ubicaron en esos barrios y los profesionales, industriales y comerciantes en el Barrio SOMISA. Esta *company town* sí estaba provista de servicios urbanos, vías de comunicación y un sistema de transporte público. Situación que podía generar tensiones y algún tipo de conflictividad.

Ante los potenciales conflictos, el Estado desarrollista del presidente Arturo Frondizi tenía previsto orientar socioeconómicamente el proceso de industrialización a nivel local. El Plan Director del año 1958 postulaba una serie de acciones; diagnosticar la situación y convertir a San Nicolás en un centro regional de circulación. Para ello se proyectó declarar zona industrial a la zona del puerto para facilitar la radicación de industrias. No obstante la instalación de nuevas pequeñas y medianas empresas, el mayor peso de SOMISA hizo que se formara un clivaje social: "somiseros/nicoleños". Los migrantes del interior (no especializados y futuros trabajadores de la empresa) aunque habitaban en los barrios de San Nicolás eran también percibidos como extraños o "somiseros". El proceso de diferenciación de la *company town* continuó hasta la crisis económica de 1975, cuando la empresa puso a la venta las viviendas del personal. Y quienes poseían un empleo en la acería duplicaban el nivel de ingresos promedio de los trabajadores de otras actividades en San Nicolás.[9]

[9] Rofman y Peñalva, p.58.

Gráfico 3 **Producción de acero en SOMISA** (miles de toneladas)



FUENTE: SOMISA, Boletín Informativo N° 29, 1989.

En el momento de mayor producción, fines de la década de 1980 (Gráfico 3), la planta de SOMISA poseía 12.000 empleos directos, más 2.000 indirectos (contratistas). La pequeña ciudad, por su efecto en otras actividades, dependía económicamente del nivel salarial y ocupacional de esos trabajadores. No obstante, a partir de 1975, la empresa poseía serias dificultades por el quiebre del modelo de sustitución de importaciones y la caída en la demanda nacional del acero. A su vez, finalizando la década de 1970, comenzó un proceso de fusiones y concentración privada (Acindar y Siderar). Coincidentemente, el Estado dejó de promocionar al sector, hubo liberalización del mercado interno, mayor presión de productos importados, lo cual motivó a la empresa a competir en el mercado externo. Esta situación coincidió con aumento de la capacidad productiva mundial y de los estándares de calidad. En el Cuadro 2 se observa cómo América latina acompañó el aumento productivo mundial.

Cuadro 2 PRODUCCIÓN DE ACERO EN LATINOAMÉRICA (miles de toneladas)

País/Año	**1983**	**1984**	**1985**	**1986**	**1987**
Argentina	2.942	2.630	2.946	3.235	3.610
Brasil	14.671	18.391	20.454	21.234	22.228
Chile	611	684	684	703	719
Colombia	463	499	500	600	705
México	6.917	7.482	7.261	7.168	7.492
Perú	289	323	490	487	503
Venezuela	2.320	2.745	3.055	3.456	3.722
Otros	370	376	380	512	568
Total	**28.583**	**33.130**	**35.770**	**37.395**	**39.547**

FUENTE: *SOMISA.* Boletin Informativo N°23, 1988.

Pero el aumento de la producción de acero no halló salida en el disminuido mercado argentino. La tasa de crecimiento en los empleados de AHZ y SOMISA muestra una caída en el ritmo de ambas empresas (Gráfico 4). En el período 1970/80 el escaso crecimiento (28,93%) del empleo en SOMISA es relativo al extraordinario 1.612% del anterior período. Este patrón, parcialmente podría ser consecuencia del impacto en el empleo causado por la crisis de la demanda nacional del acero, a partir de 1975. Sin embargo, el crecimiento intercensal en las localidades siderúrgicas Palpalá y San Nicolás no refleja la misma situación (ver Gráfico 2). Por lo tanto, el ascenso poblacional (1970/80) en Palpalá (75,43%) y San Nicolás (52,16%) podría explicarse en parte por el crecimiento propio de la Argentina (19,7%). Aunque con mayor magnitud en esas poblaciones –atrayentes de mano de obra– como había ocurrido en los censos anteriores (ver Cuadro 1).

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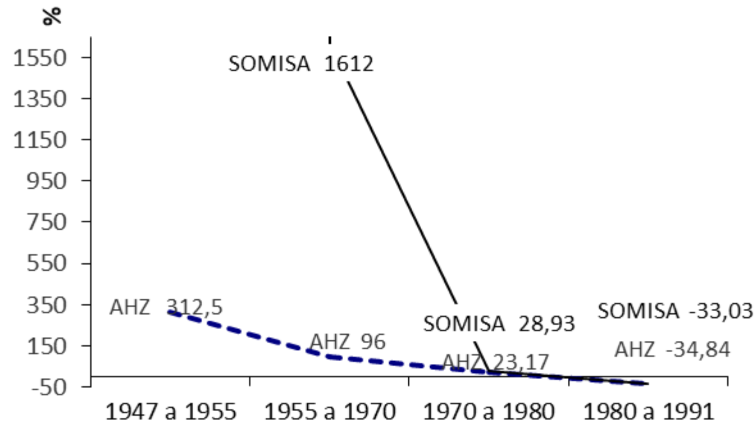
Gráfico 4 **Tasa de crecimiento de empleados Altos Hornos Zapla (AHZ) y SOMISA**



FUENTE: Elaboración propia con datos de SOMISA y Bergesio-Golovanevsky

VI. Crisis, Contexto Internacional y Privatizaciones

A partir de la década de 1940 Argentina y Brasil tuvieron como objetivo profundizar su industrialización incorporando industrias básicas. La producción siderúrgica asumía una importancia central en ese proceso. Pero el obstáculo fue la ausencia de financiamiento. La primera etapa ("liviana") de industrialización por sustitución de importaciones (ISI) iniciada en la década de 1930, coincidió con el estancamiento de los ingresos provenientes de las exportaciones de productos primarios. Esto concluía en recurrentes crisis de balance de pagos que ponían de manifiesto el desbalance comercial.

La segunda etapa de la industrialización ("pesada"), post Segunda Guerra Mundial, consistió en el desarrollo de las industrias básicas que requerían mayores inversiones. Entre estos sectores (que eran deficitarios) estaba la producción siderúrgica, de metales livianos y la química básica. El déficit económico de las empresas era cubierto por el Estado ya que, durante la guerra y la posguerra, fueron estratégicos: estaban vinculados a la defensa nacional. La respuesta a los desequilibrios económicos fue instalar un sistema productivo de plantas estatales con participación de algunas empresas privadas. [10] En Argentina las dificultades financieras llevaron a retrasar las etapas de construcción de SOMISA. A mediados de la década de 1960, ese sistema productivo, y el sector siderúrgico en particular, evidenció sus limitaciones: 1) Insuficiencia para cubrir la demanda interna en cantidad y calidad. 2) Precios finales no competitivos internacionalmente. 3) Plantas industriales fuera de las escalas técnicas y económicas de producción internacional.

A partir de 1975 en Argentina la demanda interna de acero disminuyó. Entonces el consumo nacional era de 185 kilogramos per cápita, y en 1983 apenas llegó a 98 kilogramos. Gran parte de la caída se debió a las crisis económicas, pero también porque el hierro y el acero comenzaban a ser reemplazados por otros materiales (plástico, aluminio, etc.). La salida encontrada fue aumentar las exportaciones. En 1983 Argentina vendió a EE.UU. 250 mil toneladas de acero. A principios de 1985 se exportaron a China y Venezuela 15.000 toneladas de tochos. También se vendieron palanquillas de acero a Nigeria. Así fue como 1985 arrojó un saldo exportador de 1.300.000 toneladas de acero (130% de aumento en relación a 1984).

Pero las nuevas exportaciones –que buscaban reubicar los productos en el exterior por el disminuido mercado interno– tenían escaso margen de rentabilidad.[11] En febrero de 1986, llegaron noticias que funcionarios del gobierno de Raúl Alfonsín pretendían vender SOMISA. Al terminar ese año la empresa había exportado más de 520.000 toneladas de palanquillas y chapas en caliente y frío. Esta cifra representaba casi el 60% de las exportaciones siderúrgicas argentinas. Los países importadores fueron EE.UU. Comunidad Económica Europea, Japón, China, India, Tailandia, Grecia, Paraguay y Uruguay.

[10] El paquete accionario de SOMISA estaba integrado por el Estado (DGFM), Industriales siderúrgicos y suscripción pública. El Estado nacional –según el primer Ejercicio de SOMISA, 1947/48– aportó 11,2 millones de pesos (81% del capital). Los industriales aportaron 1,2 millones y otros 1,3 millones por suscripción pública. En 1961 el Congreso Nacional posibilitó ampliar las acciones del sector privado. El Estado "podrá ofrecer a la suscripción pública sus acciones hasta el límite del noventa por ciento (90 %) del capital suscrito de la sociedad". Ver ley Nº 15.801, artículo 8º, promulgación 27 de enero de 1961. Esta ley sustituyó varios artículos de la ley 12.987 de 1947 (ley Savio).

[11] Primo, pp. 171-72.

Durante febrero de 1987 SOMISA exportó a EE.UU. (5.500 toneladas de bobinas en caliente y 5.000 toneladas de bobinas en frío); a Japón (8.700 toneladas de bobinas en caliente) y a Tailandia (15.000 toneladas de chapas gruesa). Ese mismo año, más del 50% del acero producido en SOMISA ingresó al mercado local por empresas que terminaban el proceso fabricando alambres, barras, perfiles, chapas, galvanizadores, etc. De este modo, muchas empresas argentinas, también participaban en los mercados internacionales.[12]

En el marco de esta tendencia siderúrgica se dio una disminución de las economías centrales en la producción mundial, y un significativo incremento de la participación de los países periféricos. Entre 1985 y 1989 los países centrales declinaron su participación en la producción mundial de acero del 65,5% al 50,2%. Mientras los países periféricos incrementaron su parte del 4,1% al 11,9%. En América Latina esta tendencia se debió al bajo costo relativo de la energía y de la mano de obra.[13]

Los cambios en la industria argentina hicieron que la demanda siderúrgica en los años ochenta fuese menor a las previsiones realizadas. Y los acuerdos comerciales iniciados por los presidentes Raúl Alfonsín (Argentina) y José Sarney (Brasil) favorecerían a la competitiva oferta brasileña de acero, en perjuicio de la producción Argentina. En cierto sentido se cumplía (pero previa decisión del Estado) la polémica declaración –en 1980– de un secretario del ministro argentino Alfredo Martínez de Hoz: el mercado, y no el Estado, debía decidir si el país fabricaría "caramelos o acero".[14]

A fines de 1989, recién asumido el gobierno de Carlos Menem, SOMISA, "en aras de la *revolución productiva* se lanzó a una escala de producción del 90/95% de su capacidad instalada". Y, según podemos corroborar, alcanzó los niveles más elevados de su historia (ver Gráfico 3). Pero acumulando *stocks* sin comercializar –cuando "no se vendía nada"–, lo cual agravó la deficitaria situación financiera de la empresa.[15]

En 1990 SOMISA representaba más del 50% de las exportaciones siderúrgicas argentinas, transformándose en un competidor local importante. El gobierno en ese momento cambió el signo de su política económica, adecuándose a la corriente del liberalismo mundial. Y SOMISA fue sujeta a privatización (Decreto 1398/90), ante un informe de la consultora Braxton Associates que advertía el déficit financiero de la empresa, su tamaño relativamente grande y la "venta de gran número de empresas productoras de acero en el mercado mundial". La consultora recomendaba al gobierno argentino: a) "El negocio es no competitivo en el mercado de exportación". b) "Reducciones del staff a un nivel de 5.500 trabajadores (…) pero a un nivel *clase internacional*, implicaría una fuerza de trabajo deseable de alrededor de 3.500 trabajadores para la operación de un solo alto horno".[16]

Por los resultados observados se puede afirmar que esas recomendaciones fueron aplicadas. La empresa instrumentó un plan de retiros voluntarios, acordados por el interventor, Jorge Triaca, y los sindicatos. Del total de los trabajadores (12.000) 6.245 pasaron a retiro. El 73% (4.608) eran residentes de San Nicolás, lo cual impactó fuertemente en el tejido social del pueblo. Durante treinta años la economía local había recibido los beneficios de miles de trabajadores con altos niveles de consumo. A partir de los retiros hubo un impacto regresivo: aperturas y cierres de emprendimientos improvisados en San Nicolás (pedidos de habilitación para 900 kioscos y 1.230 canchas de paddle), desocupación, pobreza y migración.

En el segundo semestre de 1992, al concretarse la transferencia al sector privado de Altos Hornos Zapla y de SOMISA, se inició una nueva fase prevista por la consultora Braxton: la etapa siderúrgica de concentración económica y achicamiento de personal. AHZ tuvo como comprador a un consorcio cuyo accionista mayoritario era Citicorp, pasando a denominarse Aceros Zapla S. A. Por su parte, la privatización de SOMISA conllevó una transformación radical en la configuración de la oferta siderúrgica argentina (ver Cuadro 3), con participación de capitales internacionales.

[12] Ibídem, pp, 182-83.
[13] Al iniciar la década de 1990 el salario medio siderúrgico en EE.UU era 25 dólares/hora mientras que en Latinoamérica era 6 dólares/hora. Aspiazu, Basualdo y Kulfas, p. 3.
[14] Schvarzer, p. 327.
[15] Rofmany Peñalva, p 62.

[16] Developing a Strategy for the Turnaround, Restructuring and Privatization of Sociedad Mixta Siderurgia Argentina (SOMISA), Braxton Associates, October, 1991. Ver Rofman y Peñalva, p. 64.

Cuadro 3 PRIVATIZACIONES EN LA INDUSTRIA SIDERÚRGICA ARGENTINA

Empresa	millones U$S	Fecha	Empresas adquirentes	País
Altos Hornos Zapla (AHZ)	33	Jul. 1992	Citicorp	EE.UU.
			Aubert Duval S.A.	Francia
			Societe Industrielle	Francia
			Pensa S.A.	Argentina
			Penfin S.A.	Argentina
SOMISA	140	Nov. 1992	Propulsora siderúrgica	Argentina
			Usiminas	Brasil
			Cía Vale do Rio Doce (CVRD)	Brasil
			Cía de Aceros Pacífico	Chile
			Banco Chartered	Gran Bretaña

FUENTE: Aspiazu, Basualdo y Kulfas, p. 47.

En el plano empresarial el grupo Techint[17] pasó a ejercer el control de la empresa privatizada. Aceros Paraná S.A. (denominación del consorcio comprador de SOMISA) dejó de elaborar productos no planos y se integró verticalmente con Propulsora Siderúrgica S.A., del mismo Grupo Techint (que poseía el 69% del paquete accionario del consorcio comprador).

En el plano social ya vimos las consecuencias de los retiros voluntarios en San Nicolás, por la privatización de su planta siderúrgica. En Palpalá ocurrió algo semejante, pero con características propias. El proceso de expansión iniciado por AHZ en la década de 1940 alcanzó su plenitud a mediados de la década de 1980. La primera etapa –producción de arrabio– llegó hasta fines de los años 60 para iniciar una segunda etapa de aceros semiterminados. Esta culmina aproximadamente en 1985 iniciando una tercera etapa cuando declina la producción y cae el empleo.

Las empresas siderúrgicas estatales brasileñas siguieron un plan de privatizaciones, que coincidió temporalmente con el argentino (Cuadro 4). Esto se explica por una tendencia mundial de fusiones y concentración de empresas.

[17] Fundado en Milán (1945) por Agostino Rocca, asesor siderúrgico del gobierno italiano durante la Segunda Guerra Mundial. Estableció buenos vínculos comerciales con América y se instaló en Argentina (1947).Ganó la licitación pública para la provisión de caños del primer gasoducto argentino: Comodoro Rivadavia-Buenos Aires. Ver Castro, p. 89.

Cuadro 4 PRIVATIZACIONES EN LA INDUSTRIA SIDERÚRGICA BRASILEÑA

Empresa	millones U$S	Fecha	Principales adquirentes	País
Usiminas	1.941,20	Oct. 1991	Fundaciones 27%, financieras 15%, CVRD 10%, empleados 10%, Bozano 7%	Brasil
CST	353,6	Jul. 1992	Bozano, Unibanco, CVRD	Brasil
CSN	1495,3	Abr. 1993	Bamerindus, Itaú, Docenave Vicunha, CVRD, empleados 20%	Brasil
Cosipa	585,7	Ago. 1993	Bozano, Anquila y Brastubo	Brasil
Açominas	598,6	Sep. 1993	Cia. Min. Part. Industrial	Brasil

FUENTE: Amarante de Andrade et al., p. 3, Revista BNDES, p. 89.

El proceso de privatizaciones mundiales se inició en el año 1987, con la venta de Aceros Pacífico (Chile). En 1988 le siguieron NZ Steel (Nueva Zelandia), British Steel (Gran Bretaña), Outokumpu (Finlandia) y POSCO (Corea del Sur). En Brasil, hasta finales de los año 80, el sector siderúrgico estuvo compuesto por más de 30 empresas o grupos que poseían protección estatal. Pero, a principios de la década de 1990 –por la cantidad y envergadura de las empresas– este país alcanzó el primer lugar en las privatizaciones mundiales (ver Cuadro 5).

Cuadro 5 INDUSTRIA SIDERÚRGICA MUNDIAL
PRIVATIZACIONES 1990-1993 (mill. dólares)

País	Empresa	Fecha	Monto	Total
Africa del Sur	ISCOR	Nov. 1991	1.370	1.370
Argentina	AHZ	Abr, 1992	33	
	SOMISA	Oct. 1992	152	185
Brasil	Usiminas	Oct. 1991	1.961	
	Piratini	Feb. 1992	108	
	Tubarao	Jul. 1992	347	
	Acesita	Oct. 1992	465	
	CSN	Abr. 1993	1.488	
	Cosipa	Ago. 1993	562	
	Acominas	Set. 1993	598	5.529
Italia	Piombino	Set. 1992	312	
	Cogne	May.1993	89	401
México	Nacional	Mar. 1991	42	
	AHMSA sur	Oct. 1991	80	
	AHMSA	Nov. 1991	145	
	Sicartsa	Nov. 1991	170	
	Sibalsa	Nov. 1991	25	462
Noruega	Norsk Jernverk	May.1990	82	82
Total				**8.029**

FUENTE: Mendes de Paula, p. 96.

Así el sector pudo reestructurarse, ampliar su capacidad de producción, quedando nueve empresas responsables del 96% de la producción brasileña: CSN, Usiminas/Cosipa, Acesita/CST, Belgo Mineira/Mendes Júnior y Gerdau/Açominas.[18]

Las privatizaciones en Brasil tuvieron antecedentes durante la crisis económica del gobierno de José Sarney (1985-1990). Pero fueron impuestas bajo la "Reforma del Estado" del presidente Fernando Collor de Mello (1990-1992). La privatización más

[18] Hasta 1991, más del 75% de la producción del acero brasileño era de propiedad estatal. Brasil era el octavo productor mundial de acero cuando privatizaron sus empresas. Luego el capital privado ejerció el control, especialmente con participación de Cía Vale do Rio Doce (CVRD) y Grupo Bozano, pero también con empleados accionistas. Amarante de Andrada, pp. 74, 84.

significativa fue la de Usiminas, un complejo industrial del acero, ubicado en Minas Gerais. Tras su realización, en octubre de 1991, se privatizaron seis empresas del acero (Cuadro 5). Era un contexto político mundial que preanunciaba un fin de ciclo: rebeliones en los países socialistas, derribamiento del muro de Berlín, implosión de la Unión Soviética. Entonces, en América latina hubo consenso político para que los Estados abandonasen la industrialización por sustitución de importaciones, y realizaran reformas económicas liberales.

VII. Conclusion

Con el objetivo de comparar cómo se desarrolló el proceso siderúrgico en Argentina y Brasil se pueden resumir algunos aspectos. En primer lugar la influencia del contexto político internacional. La evolución de los acontecimientos de la Segunda Guerra Mundial hizo que Alemania pasara –por decisión de los EE.UU– de ser rival económico a enemigo real en América del Sur. Brasil, por su posición geográfica, tenía importancia estratégica para el desarrollo de las operaciones aéreas estadounidenses. Fue en ese momento oportuno que pudo conseguir el financiamiento necesario, y así desarrollar su industria siderúrgica.

Argentina, por su parte, también había iniciado un proceso industrial "liviano", y proyectaba desarrollar industrias básicas con fines de Defensa, entre ellas el acero. Se iniciaron gestiones a fin de adquirir los elementos requeridos para el complejo industrial. Pero, decisiones políticas del Departamento de Estado obstaculizaron el intento argentino de alcanzar cierta autarquía industrial en materia de Defensa. Prefirieron reforzar su alianza con Brasil, Las razones no sólo eran estratégicas y por reciprocidad durante la Guerra Mundial, sino también por la ausencia de complementariedad económica con Argentina (que continuaba dependiendo de las exportaciones hacia Europa). También la financiación estadounidense al PSA fue demorada por problemas de la economía argentina.

Al finalizar la década de 1980 hubo un cambio de ciclo histórico mundial. El derrumbe de los sistemas socialistas trajo como consecuencia el avance de las políticas económicas neoliberales. Argentina giró rápidamente a favor de los mercados y del empresariado internacional, con aperturas comerciales y privatizaciones de empresas estatales. El sector siderúrgico pasó del estatismo sustitutivo-atrayente de empleo (crecimiento de pequeñas poblaciones) al privatismo-expulsor de empleo (decrecimiento de pequeñas poblaciones).

Podría establecerse una comparación entre CSN y sus homólogas del PSA, desde el inicio de una ciudad empresa (*company town)* hasta la crisis del empleo. En primer lugar se observa que, dichas empresas siderúrgicas, tuvieron gran influencia en el aumento de la población de pequeñas poblaciones rurales (Volta Redonda, Palpalá y San Nicolás). Las tasas de crecimiento y decrecimiento poblacional gráficamente son similares. El impulso inicial de las siderúrgicas estatales generó no sólo atracción de mano de obra industrial, sino también aumento de actividades empresarias proveedoras (industriales o comerciales). Así surgió una *company town* siderúrgica brasileña, cuyo modelo de viviendas tuvo las características del *Estado Novo* de Getulio Vargas. Mientras, el correspondiente paradigma argentino fue marcado por la impronta del sistema militar (nacional-desarrollista), ideado por el general Manuel Savio. Pero ese modelo estatal sufrió un fuerte golpe al inicio de la década de 1980: caída en las inversiones, ajustes y despidos de empleados. Las consecuencias fueron similares en ambos países. En Brasil la crisis económica se reflejó en la disminución del crecimiento de Volta Redonda, comparando con el censo del período anterior (1970/1980). La magnitud de la caída entre 1970 y 1991 (42, 82%) fue superior a San Nicolás (40%) pero inferior al 57% de Palpalá.

El impacto de la reestructuración siderúrgica en Brasil y Argentina podemos evaluarlo en las privatizaciones de sus empresas, que tuvieron características diferentes. En Brasil gran parte de las acciones empresarias pasaron a manos de los empleados. En Argentina eso no ocurrió, aunque –a diferencia del modelo brasileño– la participación del capital extranjero fue mayor. Ambos países compartieron despidos, desaparición de las *company town* y desempleo. Pero hay otras variables vinculadas por considerar: la relación del desempleo en las localidades pequeñas y la migración. También el aumento de la población y la pobreza en las grandes urbes cercanas (Río de Janeiro, Rosario, San Salvador de Jujuy).

A modo de resumen. El desarrollo siderúrgico en Argentina y Brasil formó parte de las políticas de defensa de los Estados en el contexto de un mundo en guerra. Cuando la economía, la industrialización, el trabajo y el orden social eran componentes de las estrategias militares. El fin de la Guerra Fría entre las grandes potencias –con la implosión de la Unión soviética– significó el fin de las políticas estatales de bienestar social en la mayoría de los países. Las privatizaciones trajeron relocalización de los capitales internacionales y mayor concentración empresarial. También, relocalización de los desempleados, concentración alrededor de las grandes urbes y decrecimiento en las pequeñas. Estas fueron algunas consecuencias sociales de la globalización económica.

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Coupled Error Dynamic Formulation for Modal Control of a Two Link Manipulator having Two Revolute Joints

By Natraj Mishra
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Abstract- In the present work, reformulation of the dynamics of a planar two-link manipulator has been presented in the form of joint errors and their derivatives. The linear second-order differential equations with time-varying coefficients represent the Coupled Error Dynamics of the system. In these equations, the non-linear centrifugal and Coriolis terms are expressed as linear functions of joint error rates and the non-linear gravity terms as a linear function of joint errors with time-varying coefficients. After inclusion of linearized version of these terms, the concept of modal analysis is used in the design of a control system for the robot. The developed control approach is compared with the commonly used computed-torque control approach, as applied for a high-speed direct-drive two-link manipulator with revolute joints. Thus in the proposed approach for controller design, the system non-linearities are taken as part of the system representation itself instead of disturbances as assumed in existing approaches.

Keywords: *coupled error dynamics, computed-torque control, modal analysis, rigid robot, IMSC.*

GJRE-G Classification: *DDC Code: 332.041 LCC Code: HB501*

COUPLEDERRORDYNAMICFORMULATIONFORMODALCONTROLOFATWOLINKMANIPULATORHAVINGTWOREVOLUTEJOINTS

Strictly as per the compliance and regulations of:

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Natraj Mishra

Abstract- In the present work, reformulation of the dynamics of a planar two-link manipulator has been presented in the form of joint errors and their derivatives. The linear second-order differential equations with time-varying coefficients represent the Coupled Error Dynamics of the system. In these equations, the non-linear centrifugal and Coriolis terms are expressed as linear functions of joint error rates and the non-linear gravity terms as a linear function of joint errors with time-varying coefficients. After inclusion of linearized version of these terms, the concept of modal analysis is used in the design of a control system for the robot. The developed control approach is compared with the commonly used computed-torque control approach, as applied for a high-speed direct-drive two-link manipulator with revolute joints. Thus in the proposed approach for controller design, the system non-linearities are taken as part of the system representation itself instead of disturbances as assumed in existing approaches.

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Highlights

- Reformulation of robot dynamic equations in the form of joint errors.
- Use of modal control to derive control gains.
- Demonstration of efficient trajectory tracking.

I. Introduction

The dynamics of a planar two-link rigid robot having two revolute joints is non-linear and involves coupling between joint variables. Linear control is difficult to apply to such systems. In order to apply linear control theory for joint motion control of robots, a high gear ratio is used so that a linear PD or PID controller may be used. A computed-torque controller is a better controller than a linear PD or PID controller. It is a special application of 'feedback linearization' of non-linear systems and computed-torque like controls appear in robust control, adaptive control etc. [1]. The motion of the joints of a robot can be controlled either by the approach of 'independent joint control' or by the approach of 'multivariable control' [2]. In 'independent joint control,' each joint of a robot is controlled as a single input/single-output (SISO) system. The coupling effects due to the motion of other links are treated as disturbances. On the other hand, the multivariable control facilitates the design of robust [3] and adaptive [4] nonlinear controllers that guarantee more stability and better tracking of arbitrary trajectories. Harris and Wang [5] have proposed mathematical models for the stabilization of closed-loop constrained robots. Slotine and Yang [6] have presented a computationally efficient time-optimal path-following algorithm for robots under actuator constraints. Few authors have made use of the concept of decoupled and invariant dynamics of manipulators during the design stage for achieving high-speed trajectory control of direct-drive manipulators [7] and the concept of dynamic isotropy for decoupling of inertia matrix for obtaining robust control [8]. A number of research works including Piazzi and Visioli [9], Constantinescu and Croft [10], Gasparetto and Zanotto [11] and Marcello et al. [12] have have focused on formulating algorithms based on minimization of an objective function that helps in finding the time-optimal trajectories for the robots. Xavier et al. [13] have described how to build autonomous robots that can perform service tasks safely within the vicinity of humans. Machado et al. [14] have suggested that although direct design algorithm and computed torque controllers are superior to linear controllers, classical design approach can be implemented practically. This approach can be used to analyze and develop nonlinear model-based controllers for robots. Shiller and Chang [15] have proposed a method that helps in the reduction of tracking errors for high-speed articulated robots. This is achieved by preshaping the actual trajectory of the robot by using inverse control gains. Gradient search method is used to find the optimized control parameters for trajectory preshaping. Karger et al. [16] have proposed a hyperbolic trajectory for any degrees of freedom robot. The advantage of this trajectory is that it can be planned both in Joint space and Cartesian space with the requirement of inverse kinematics only at the initial and final positions. The hyperbolic trajectory also evades any obstacle successfully that lies between these two points. Ouyang et al. [17] have tracked the trajectory of a real-time controllable mechanism using the approach of force balancing. Force balancing is achieved by a novel approach referred to as adjusting kinematic parameter (AKP) and it facilitates the tracking of trajectory efficiently by controllers. The authors have compared the AKP approach with PD and non-linear PD

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approach and concluded that it's more promising. Afzali-Far et al. [18] have addressed the problem of design of a 3-DOF Gantry Tau robot using the concept of dynamic isotropy for the first time. This concept can be used to optimize the geometry of robots. The authors have also investigated upon Jacobian and stiffness matrices. Analytical solutions are provided to obtain both a decoupled stiffness matrix and dynamic isotropy condition. Arakelian et al. [19] have used the concept of decoupled dynamics for designing a 2-DOF exoskeleton arm. By doing so, the task of controller design gets simplified. The dynamic equations of the exoskeleton arms are decoupled by using epicyclic gear train. The parameters of the gear train are determined based upon the elimination of nonlinear terms in the mechanical energy equations of the manipulator. This results in redistribution of masses due to which the joint actuator torque becomes a linear function of angular acceleration. In another research, Arakelian et al. [20] have achieved the dynamic decoupling of a serial manipulator by using adjustable links and an optimal control technique. Their approach takes into account the effect of changing payload. The proposed approach transforms a nonlinear system into a linear system without the use of feedback linearization. The adjustable links play an effective role in cancelling the nonlinear terms present in the mechanical energy expression of the manipulator. Pham et al. [21] have performed the trajectory planning using path-velocity decomposition method. This involves two steps: finding a configuration space path that satisfies the geometric constraints and time-parametrization of the same path such that it satisfies the kinodynamic constraints. Based upon this method, the authors have proposed a new algorithm- Admissible Velocity Propagation. This method is useful for truly dynamic motions that cannot be handled well by quasi-static methods. Al-Gbouri et al. [22] have addressed the issue of stability of robust control systems employing feedback linearization. The method used by the authors is referred to as the gap metric robust stability analysis. The novel control law used by them helps to classify the system nonlinearity into stable and unstable components. The controller cancels the unstable linear component of the plant. Robust performance margins have been derived and the new approach yielded better results than other methods like small gain theorem. Asif et al. [23] have addressed the two main issues of accurate and precise control of a robotic arm using the approach of inverse kinematics and linear control law. The authors have compared the performance of three different types of control laws viz. PID, pole-placement and LQR. They have concluded that LQR gave the best results. Hwang et al. [24] have specified design parameters for a seven degree of freedom serial manipulator. These design parameters have been obtained using various performance indices. These performance indices are related to distribution of inertia, dexterity and energy. They correspond to workspace, kinematics and dynamics respectively for the manipulator. The design parameters were optimized using genetic algorithm. Arakelian et al. [25] have presented a review of important methods used for achieving dynamic decoupling of robots. The three main methods are: mass redistribution, actuator relocation and addition of auxiliary links. In the first method, gears are used as counterweights while in the second method, an epicyclic gear train is used. The authors have stated that the third method was the optimal one. The effect of changing payload is the least studied area. They have emphasized that for effective dynamic decoupling, it is required to develop solutions that are amalgamation of both the mechanical and control approaches. Huang et al. [26] have presented a methodology to optimally plan the trajectory of robots. The trajectory has been obtained in joint space using 5th order B-spline and optimized using non-dominated sorting genetic algorithm (NSGA-II). The trajectory satisfied the continuity of jerk. The objective functions for NSGA-II included the travelling time and mean jerk along the complete trajectory. Liu et al. [27] have have improved the tracking precision of end-effector of a robot by proposing a trajectory planning technique that yielded stable movement. For this, firstly the kinematic and dynamic models have been established using the screw theory and Kane's method. The error at the end-effector was minimized by using PSO algorithm and joint flexibilities. Routa et al. [28] have proposed a new technique for optimal planning of trajectory for welding robots. For this, they have used Teaching Learning Based Optimization algorithm that made use of minimization of jerk and travel time. Hou and Mason [29] have developed a criteria that might help in maintaining the contacts required for robotic manipulation. These criteria are robust to 'model uncertainties' and 'disturbing forces'. They have analyzed three different types of contact modes: sticking, sliding and disengaging. Friedrich and Martin Buss [30] have tried to achieve the robust stability of manipulators when their feedback control law was modified through online mode. They have characterized the robust controllers for rigid robots utilizing the approximate inverse dynamics control approach. A double-Youla parametrization technique was applied for characterization of robust controllers for robots used for machining of sculptured surfaces. Lua et al. [31] have considered constraints like tool-tip kinematic constraints and curved tool path in joint space. Machining of sculptured surfaces require high accuracy, so authors have used Pontryagin maximum principle as the solver.

From the present survey on trajectory control of robot manipulators it is found that for performing desired tasks, it is necessary to plan trajectories optimally. This can be done in three ways; *viz.,* minimum-time trajectory planning, minimum-energy trajectory planning and

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minimum-jerk trajectory planning. It is also found that dynamic decoupling of system dynamics makes it easy to design a good control system. Furthermore, the sensitivity of unmodelled dynamics and bounds on actuator are the key issues in controller design [32] for good trajectory control. Design for Control approach [33] may help in improving the performance of controllers significantly. It involves the scheme of redistribution of masses of the mechanical structure under consideration that may help in improving the performance of controller to be used in electromechanical systems. Current research is focussed on design of controllers based upon accurate dynamic modelling of the physical systems under consideration. The design of such controllers makes use of concept of modal control theory. Cambera et al. [34], Rong et al. [35], Shen et al. [36] and Zhao et al. [37] have all highlighted the performance characteristics of such controllers through their research.

The current work presents a distinctive way of expressing the dynamics of a Two-Link rigid robot. The dynamic equations of the robot are re-written in the form of joint errors and involve coupling between errors in joint variables. These equations are expressed in the form of linear second-order differential equations with time-varying coefficients and referred to as Coupled Error Dynamics (CED). Based upon this reformulated dynamics, a scheme for finding proportional-derivative (PD) control gains is obtained that may be applicable to high-speed direct-drive manipulators.

II. Mathematical Modelling

The dynamics of a planar two-link rigid robot (Fig. 1) having two revolute joints is well explained in various text books on Robotics [1,2,42,43]. After considering the effects of payload and joint inertias, the matrix equation of motion of a two-link robot with revolute joints and a payload is given as follows.

$$\begin{Bmatrix}\tau_1\\ \tau_2\end{Bmatrix} = \begin{bmatrix}M_{11} & M_{12}\\ M_{21} & M_{22}\end{bmatrix}\begin{Bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\end{Bmatrix} + \begin{bmatrix}N_1\\ N_2\end{bmatrix} + \begin{bmatrix}G_1\\ G_2\end{bmatrix} \tag{1}$$

where, τ_1 and τ_2 are joint torques, θ_1 and θ_2 are joint angles and

$$M_{11} = (m_1 + m_2)L_1^2 + m_2L_2^2 + 2m_2L_1L_2\cos\theta_2 + I_{h1} + M_p(L_1^2 + L_2^2 + 2L_1L_2\cos\theta_2) + m_{h2}L_1^2$$

$$M_{12} = M_{21} = m_2L_2^2 + m_2L_1L_2\cos\theta_2 + M_p(L_1L_2\cos\theta_2 + L_2^2)$$

$$M_{22} = m_2L_2^2 + I_{h2} + M_pL_2^2 \tag{1a}$$

$$N_1 = -m_2L_1L_2\left(2\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_2^2\right)\sin\theta_2 + M_pL_1L_2\left(2\dot{\theta}_1\dot{\theta}_2 - \dot{\theta}_2^2\right)\sin\theta_2$$

$$N_2 = m_2L_1L_2\dot{\theta}_1^2\sin\theta_2 - 2M_pL_1L_2\sin\theta_2\,.\,\dot{\theta}_1\dot{\theta}_2 \tag{1b}$$

$$G_1 = \left(m_1 + m_{h2} + m_2 + M_p\right)gL_1\cos\theta_1 + \left(m_2 + M_p\right)gL_2\cos(\theta_1 + \theta_2)$$

$$G_2 = \left(m_2 + M_p\right)gL_2\cos(\theta_1 + \theta_2) \tag{1c}$$

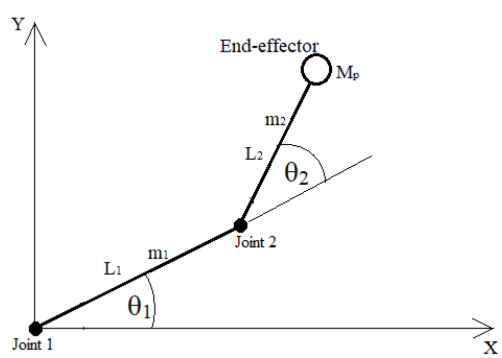

Fig. 1: A Two-Link Rigid serial robot having two Revolute Joints in X-Y plane

In equation (1), m_1 and m_2 are masses of Link-1 and Link-2 respectively, L_1 and L_2 are lengths of Link-1 and Link-2 respectively, I_{h1} and I_{h2} are joint/hub mass moment of inertias at Joint-1 and Joint-2 respectively, m_{h2} is the mass of hub of Joint-2 and M_p is mass of payload attached at the end of Link 2, i.e., at the end-effector. M_{11}, M_{12}, M_{21} and M_{22} are the elements of inertia matrix, N_1 and N_2 are the elements of centrifugal/Coriolis torque vector and G_1 and G_2 are the elements of the gravity torque vector. It can be seen from equation (1) that the mass matrix is coupled and depends upon the configuration of the manipulator. This makes the control problem difficult. To reduce this difficulty, Youcef and Harushiko [38] presented a design scheme that diagonalizes the mass matrix and also makes it configuration-invariant. In this work, a different approach is used which makes use of the original inertia of the robot.

A robot is designed to move along the desired trajectory for performing an assigned task. Thus, the desired joint angles are θ_{1d} for Joint 1 and θ_{2d} for Joint 2. The joint errors will be as follows.

$$\theta_{je} = \theta_{jd} - \theta_j \tag{2}$$

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where, *j* represents the joint number (=1, 2), subscript-'e' stands for 'error' and subscript-'d' stands for 'desired'. Next, we substitute for actual joint angles θ_1, θ_2 and their derivatives from equation (2) into equation (1).

Firstly, we analyze the centrifugal/Coriolis' torque terms represented by N_1 and N_2.

a) Analysis of Centrifugal/Coriolis Terms

Equation (1b) can be re-written as:

$$N_1 = 2L_1L_2 \sin\theta_2 \left[(M_p - m_2)\dot\theta_1\dot\theta_2 - (m_2 + M_p)\dot\theta_2^2\right]$$

$$N_2 = 2L_1L_2 \sin\theta_2 \left[m_2\dot\theta_1^2 - 2M_p\dot\theta_1\dot\theta_2\right] \qquad (1b)$$

Using equation (2), we can write:

$$\dot\theta_1\dot\theta_2 = (\dot\theta_{1d} - \dot\theta_{1e})(\dot\theta_{2d} - \dot\theta_{2e}) = \dot\theta_{1d}\dot\theta_{2d} - \dot\theta_{1d}\dot\theta_{2e} - \dot\theta_{1e}\dot\theta_{2d} + \dot\theta_{1e}\dot\theta_{2e}$$

$$\dot\theta_1^2 = (\dot\theta_{1d} - \dot\theta_{1e})^2 = \dot\theta_{1d}^2 + \dot\theta_{1e}^2 - 2\dot\theta_{1d}\dot\theta_{1e}$$

$$\dot\theta_2^2 = (\dot\theta_{2d} - \dot\theta_{2e})^2 = \dot\theta_{2d}^2 + \dot\theta_{2e}^2 - 2\dot\theta_{2d}\dot\theta_{2e}$$

$$\sin\theta_2 = \sin(\theta_{2d} - \theta_{2e}) = \sin\theta_{2d}\cos\theta_{2e} - \cos\theta_{2d}\sin\theta_{2e}$$

Substituting above expressions in equation (1b) we get

$$N_1 = 2L_1L_2(\sin\theta_{2d}\cos\theta_{2e} - \cos\theta_{2d}\sin\theta_{2e})[\{(M_p - m_2)\dot\theta_{1d}\dot\theta_{2d} - (m_2 + M_p)\dot\theta_{2d}^2\} + \{(m_2 - M_p)\dot\theta_{1d} + 2(m_2 + M_p)\dot\theta_{2d}\}\dot\theta_{2e} - (M_p - m_2)\dot\theta_{2d}\dot\theta_{1e} + (M_p - m_2)\dot\theta_{1e}\dot\theta_{2e} - (m_2 + M_p)\dot\theta_{2e}^2]$$

$$N_2 = 2L_1L_2(\sin\theta_{2d}\cos\theta_{2e} - \cos\theta_{2d}\sin\theta_{2e})[\{m_2\dot\theta_{1d}^2 - 2M_p\dot\theta_{1d}\dot\theta_{2d}\} + m_2\dot\theta_{1e}^2 - 2M_p\dot\theta_{1e}\dot\theta_{2e} + (-2m_2\dot\theta_{1d} + 2M_p\dot\theta_{2d})\dot\theta_{1e} + 2M_p\dot\theta_{1d}\dot\theta_{2e}]$$

Assuming θ_{2e} to be very small, we can replace $\sin\theta_{2e}$ by θ_{2e} and $\cos\theta_{2e}$ by 1. Furthermore, for small joint errors and small joint error rates, we obtain

$$N_1(t) = A(t) - \left(\frac{\partial A(t)}{\partial\theta_{2d}(t)}\right)\theta_{2e}(t); \qquad N_2(t) = B(t) - \left(\frac{\partial B(t)}{\partial\theta_{2d}(t)}\right)\theta_{2e}(t) \qquad (3)$$

In above expressions,

$$A(t) = N_{1d} - 2L_1L_2\sin\theta_{2d}\left[\left(\frac{\partial\beta}{\partial\dot\theta_{1d}}\right)\dot\theta_{1e} + \left(\frac{\partial\beta}{\partial\dot\theta_{2d}}\right)\dot\theta_{2e}\right] \qquad (3a)$$

$$B(t) = N_{2d} - 2L_1L_2\sin\theta_{2d}\left[\left(\frac{\partial\gamma}{\partial\dot\theta_{1d}}\right)\dot\theta_{1e} + \left(\frac{\partial\gamma}{\partial\dot\theta_{2d}}\right)\dot\theta_{2e}\right] \qquad (3b)$$

$$\beta(t) = (M_p - m_2)\dot\theta_{1d}\dot\theta_{2d} - (m_2 + M_p)\dot\theta_{2d}^2 \qquad (3c)$$

$$\gamma(t) = m_2\dot\theta_{1d}^2 - 2M_p\dot\theta_{1d}\dot\theta_{2d} \qquad (3d)$$

The terms, N_{1d} and N_{2d} can be obtained by replacing θ_1 by θ_{1d} and θ_2 by θ_{2d} in equation (1b).

b) Analysis of Inertia Terms

From equation (1), the inertia torques can be written as:

$$\begin{Bmatrix} IF_1 \\ IF_2 \end{Bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{Bmatrix} \ddot\theta_1 \\ \ddot\theta_2 \end{Bmatrix}$$

Using equation (2), we can write:

$$\begin{Bmatrix} IF_1 \\ IF_2 \end{Bmatrix} = \begin{Bmatrix} M_{11}(\ddot\theta_{1d} - \ddot\theta_{1e}) + M_{12}(\ddot\theta_{2d} - \ddot\theta_{2e}) \\ M_{21}(\ddot\theta_{1d} - \ddot\theta_{1e}) + M_{22}(\ddot\theta_{2d} - \ddot\theta_{2e}) \end{Bmatrix}$$

In the above expression, the inertia terms: M_{11}, M_{12}, M_{21} and M_{22} can be obtained using equation (1a). These can be reformulated as follows.

$$M_{11} = M_{11d} + \left[a_{11d}\cos\theta_{2e} - \left(\frac{\partial a_{11d}}{\partial \theta_{2d}}\right)\sin\theta_{2e}\right];$$

$$M_{12} = M_{12d} + \frac{1}{2}\left[a_{11d}\cos\theta_{2e} - \left(\frac{\partial a_{11d}}{\partial \theta_{2d}}\right)\sin\theta_{2e}\right]$$

$$M_{21} = M_{21d} + \frac{1}{2}\left[a_{11d}\cos\theta_{2e} - \left(\frac{\partial a_{11d}}{\partial \theta_{2d}}\right)\sin\theta_{2e}\right];\ M_{22} = M_{22d} \quad (4)$$

In above expressions,

$$M_{11d} = (m_1 + m_2 + m_{h2} + M_p)L_1^2 + (m_2 + M_p)L_2^2 + I_{h1};$$

$$M_{12d} = M_{21d} = (m_2 + M_p)L_2^2;$$

$$M_{22d} = (m_2 + M_p)L_2^2 + I_{h2};\ a_{11d} = 2L_1L_2(m_2 + M_p)\cos\theta_{2d} \quad (4a)$$

Using equation (1) and equation (2), the inertia torques (IF_1 and IF_2) acting at joints-1 and 2 can be written as:

$$\begin{Bmatrix} IF_1 \\ IF_2 \end{Bmatrix} = \begin{bmatrix} M_{11d} & M_{12d} \\ M_{21d} & M_{22d} \end{bmatrix}\begin{Bmatrix} \ddot{\theta}_{1d} \\ \ddot{\theta}_{2d} \end{Bmatrix} + \begin{bmatrix} \phi & \frac{\phi}{2} \\ \frac{\phi}{2} & 0 \end{bmatrix}\begin{Bmatrix} \ddot{\theta}_{1d} \\ \ddot{\theta}_{2d} \end{Bmatrix} - \begin{bmatrix} M_{11d} + \phi & M_{12d} + \frac{\phi}{2} \\ M_{21d} + \frac{\phi}{2} & M_{22d} \end{bmatrix}\begin{Bmatrix} \ddot{\theta}_{1e} \\ \ddot{\theta}_{2e} \end{Bmatrix} \quad (4b)$$

where $\phi = a_{11d}\cos\theta_{2e} - \left(\frac{\partial a_{11d}}{\partial \theta_{2d}}\right)\sin\theta_{2e}$

c) Analysis of Gravity Terms

The gravity terms are provided by equation (1c). Using equation (2), we can write:

$$\cos\theta_1 = \cos(\theta_{1d} - \theta_{1e}) = \cos\theta_{1d}\cos\theta_{1e} + \sin\theta_{1d}\sin\theta_{1e}$$

$$\cos\theta_2 = \cos(\theta_{2d} - \theta_{2e}) = \cos\theta_{2d}\cos\theta_{2e} + \sin\theta_{2d}\sin\theta_{2e}$$

$$\sin\theta_1 = \sin(\theta_{1d} - \theta_{1e}) = \sin\theta_{1d}\cos\theta_{1e} - \cos\theta_{1d}\sin\theta_{1e}$$

$$\sin\theta_2 = \sin(\theta_{2d} - \theta_{2e}) = \sin\theta_{2d}\cos\theta_{2e} - \cos\theta_{2d}\sin\theta_{2e}$$

$$\cos(\theta_1 + \theta_2) = \cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2$$

For very small values of θ_{1e} and θ_{2e}, we can write

$\cos\theta_{1e} \approx 1$; $\cos\theta_{2e} \approx 1$; $\sin\theta_{1e} \approx \theta_{1e}$, and $\sin\theta_{2e} \approx \theta_{2e}$. Thus, the gravity term can be rewritten as follows.

$$\begin{Bmatrix} G_1 \\ G_2 \end{Bmatrix} = \begin{bmatrix} G_{1d} \\ G_{2d} \end{bmatrix} + \begin{bmatrix} G_{11e} & G_{12e} \\ G_{21e} & G_{22e} \end{bmatrix}\begin{Bmatrix} \theta_{1e} \\ \theta_{2e} \end{Bmatrix} \quad (5a)$$

In the above equation,

$$G_{1d} = (m_1 + m_{h2} + m_2 + M_p)gL_1\cos\theta_{1d} + (m_2 + M_p)gL_2\cos(\theta_{1d} + \theta_{2d});$$

$$G_{2d} = (m_2 + M_p)gL_2\cos(\theta_{1d} + \theta_{2d})$$

$$G_{11e} = (m_1 + m_{h2} + m_2 + M_p)L_1\sin\theta_{1d} + (m_2 + M_p)L_2\sin(\theta_{1d} + \theta_{2d})$$

$$G_{12e} = G_{21e} = G_{22e} = (m_2 + M_p)L_2\sin(\theta_{1d} + \theta_{2d})$$

(5b)

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d) Reformulated Dynamics

Using equations- (1), (3), (4) and (5b) we can write,

$$\begin{Bmatrix}\tau_{1e}\\ \tau_{2e}\end{Bmatrix} = \begin{bmatrix} M_{11d}+\phi & M_{12d}+\frac{\phi}{2} \\ M_{21d}+\frac{\phi}{2} & M_{22d}\end{bmatrix}\begin{Bmatrix}\ddot{\theta}_{1e}\\ \ddot{\theta}_{2e}\end{Bmatrix} - 2L_1L_2(\theta_{2e}.\cos\theta_{2d} - \sin\theta_{2d})\begin{bmatrix}\frac{\partial\beta}{\partial\dot{\theta}_{1d}} & \frac{\partial\beta}{\partial\dot{\theta}_{2d}} \\ \frac{\partial\gamma}{\partial\dot{\theta}_{1d}} & \frac{\partial\gamma}{\partial\dot{\theta}_{2d}}\end{bmatrix}\begin{Bmatrix}\dot{\theta}_{1e}\\ \dot{\theta}_{2e}\end{Bmatrix} - \begin{bmatrix}G_{11e} & G_{12e}\\ G_{21e} & G_{22e}\end{bmatrix}\begin{Bmatrix}\theta_{1e}\\ \theta_{2e}\end{Bmatrix} \quad (6)$$

In the above expression,

$$\tau_{1e} = \tau_{1d} - \tau_1$$
$$\tau_{2e} = \tau_{2d} - \tau_2 \quad (6a)$$

Since, equation (6) involves coupling between the joint errors, it is termed as 'Coupled-Error Dynamics'. In equation (6a),

$$\tau_{1d} = IF_{1d} + N_{1d} + G_{1d};\ \tau_{2d} = IF_{2d} + N_{2d} + G_{2d} \quad (6b)$$

where, $IF_{1d} = M_{11d}\ddot{\theta}_{1d} + M_{12d}\ddot{\theta}_{2d};\ IF_{2d} = M_{21d}\ddot{\theta}_{1d} + M_{22d}\ddot{\theta}_{2d};\ N_{1d}$ and N_{2d} are obtained by replacing variables- θ_1 and θ_2 in equation (1b) by θ_{1d} and θ_{2d}; G_{1d} and G_{2d} are provided in equation (5b).

III. Control System Design

Luh [39] proposed the design of a conventional controller for controlling each link or joint individually. In this paper, Modal Controller is used ([40], [41]) for the control function. In equation (6) the error dynamics of a two-link rigid robot is described. In general form, this equation can be written as

$$\begin{Bmatrix}\tau_{1d}-\tau_1\\ \tau_{2d}-\tau_2\end{Bmatrix} = \begin{bmatrix}M_{e11} & M_{e12}\\ M_{e21} & M_{e22}\end{bmatrix}\begin{Bmatrix}\ddot{\theta}_{1e}\\ \ddot{\theta}_{2e}\end{Bmatrix} - \begin{bmatrix}C_{e11} & C_{e12}\\ C_{e21} & C_{e22}\end{bmatrix}\begin{Bmatrix}\dot{\theta}_{1e}\\ \dot{\theta}_{2e}\end{Bmatrix} - \begin{bmatrix}G_{11e} & G_{12e}\\ G_{21e} & G_{22e}\end{bmatrix}\begin{Bmatrix}\theta_{1e}\\ \theta_{2e}\end{Bmatrix} \quad (7)$$

Defining the control torque as:

$$\{u\} = \{\tau\} = [K_v]\{\dot{\theta}_e\} + [K_p]\{\theta_e\} \quad (8)$$

and substituting in equation (7), we get

$$[M_e]\{\ddot{\theta}_e\} + ([K_v] - [C_e])\{\dot{\theta}_e\} + ([K_p] - [G_e])\{\theta_e\} = \{\tau_d\} \quad (9)$$

In equation (9), the matrices- $[M_e]$, $[C_e]$ and $[G_e]$ are time-varying and also involve non-linear terms. It refers to the case of coupled control [41]. The values of gains- $[K_v]$ and $[K_p]$ must lie within a certain range so that the controller performance may not deteriorate even though the coefficients in equation (9) change with time. The ranges for $[K_v]$ and $[K_p]$ can be found out by designing the controller for minimum and maximum values of d and d as shown in the example below. Thereafter, the coefficients in equation (9) can be taken as constant. Now, the Eigenvalue problem for equation (9) can be written as:

$$[M_e]D^2\theta_e + ([K_p] - [G_e])\theta_e = 0 \quad (10)$$

Putting $D^2 = -\omega^2$ we get,

$$[(K_p - G_e) - \omega^2 M_e]\{\theta_e\} = 0 \quad (11)$$

Let us assume, $[K_p] = \begin{bmatrix}K_{p11} & K_{p12}\\ K_{p21} & K_{p22}\end{bmatrix}$ (12)

Now, we select $K_{p12} = G_{e12}$ and $K_{p21} = G_{e21}$.

Thus we get,

$$\left(\begin{bmatrix}K_{p11} - G_{11e} & 0\\ 0 & K_{p22} - G_{22e}\end{bmatrix} - \omega^2\begin{bmatrix}M_{e11} & M_{e12}\\ M_{e21} & M_{e22}\end{bmatrix}\right)\begin{Bmatrix}\theta_{1e}\\ \theta_{2e}\end{Bmatrix} = \begin{Bmatrix}0\\ 0\end{Bmatrix} \quad (13)$$

Using equation (13), the frequency equation can be written as follows.

$$\begin{vmatrix} K_{p11} - G_{11e} - \omega^2 M_{e11} & -\omega^2 M_{e12} \\ -\omega^2 M_{e21} & K_{p22} - G_{22e} - \omega^2 M_{e22} \end{vmatrix} = 0 \quad (14)$$

From the frequency equation described by equation (14), two Eigenvalues ω_1^2 and ω_2^2 corresponding to 'mode I' and 'mode II' respectively, will be obtained. Using these eigenvalues, the eigenvectors can be found out. The eigenvectors for 'mode I' and 'mode II' can be expressed as follows.

$$\left(\frac{\theta_{2e}}{\theta_{1e}}\right)_{\mathrm{I}} = \sqrt{\frac{K_{p11}-G_{11e}-\omega_1^2 M_{e11}}{K_{p22}-G_{22e}-\omega_1^2 M_{e22}}} = r_1; \quad \left(\frac{\theta_{2e}}{\theta_{1e}}\right)_{\mathrm{II}} = \sqrt{\frac{K_{p11}-G_{11e}-\omega_2^2 M_{e11}}{K_{p22}-G_{22e}-\omega_2^2 M_{e22}}} = r_2 \quad (15)$$

The modal matrix will now be given as:

$$[W] = \begin{bmatrix} 1 & 1 \\ r_1 & r_2 \end{bmatrix} = [\boldsymbol{W_1} \quad \boldsymbol{W_2}] \quad (16)$$

This modal matrix is ortho-normalized using the relationship: Wi'TMeWi'=1 where *i* represents the mode number and Wi'=ciWi, c_i being some constant. Subscript 'T' means 'transpose'. The orthonormalized modal matrix is thus given as:

$$[W'] = [c_1\boldsymbol{W_1} \quad c_2\boldsymbol{W_2}]; \text{ where, } c_1 = [M_{e11} + 2r_1 M_{e12} + r_1^2 M_{e22}]^{-1};$$
$$c_2 = [M_{e11} + 2r_2 M_{e12} + r_2^2 M_{e22}]^{-1} \quad (17)$$

Now, let us take: $\{\theta_e\} = [W']\{\eta_e\}$ (18)

where η_e represents the modal coordinates. The variable θ_e represents the joint error and is in global coordinates. Substituting equation (18) into equation (9) and then multiplying throughout by W'^T we get:

$$[W'^T M_e W']\{\ddot{\eta}_e\} + [W'^T(K_v - C_e)W']\{\dot{\eta}_e\} + [W'^T(K_p - G_e)W']\{\eta_e\} = [W'^T]\{\tau_d\}$$

Now, $[W'^T M_e W']$ = identity matrix and

$W'^T(K_p - G_e)W'$ = diagonal matrix containing Eigenvalues.

Thus, we get

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{Bmatrix} \ddot{\eta}_{1e} \\ \ddot{\eta}_{1e} \end{Bmatrix} + [W'^T(K_v - C_e)W']\begin{Bmatrix} \dot{\eta}_{1e} \\ \dot{\eta}_{2e} \end{Bmatrix} + \begin{bmatrix} \omega_1^2 & 0 \\ 0 & \omega_2^2 \end{bmatrix}\begin{Bmatrix} \eta_{1e} \\ \eta_{2e} \end{Bmatrix} = \begin{bmatrix} c_1 & c_1 r_1 \\ c_2 & c_2 r_2 \end{bmatrix}\begin{Bmatrix} \tau_{1d} \\ \tau_{2d} \end{Bmatrix} \quad (19)$$

Now, let us assume that, $[K_v] = \begin{bmatrix} K_{v11} & K_{v12} \\ K_{v21} & K_{v22} \end{bmatrix}$ (20)

Thus, $(K_v - C_e) = \begin{bmatrix} K_{v11} - C_{e11} & K_{v12} - C_{e12} \\ K_{v21} - C_{e21} & K_{v22} - C_{e22} \end{bmatrix}$ (21)

Since [C_e] is time-varying in nature, the matrix (K_v-C_e) will also be time-varying. It has been mentioned earlier that our task is to design a controller whose performance may not deteriorate due to a change in system parameters. For this, we design for either maximum or minimum values of d and d. The joint error θ_{2e} in equation (6) may be neglected if it is too small or otherwise its maximum allowable value may be used while designing the robotic system. In that case, the C_e matrix can be taken as constant and we shall obtain a range for gain K_v. The off-diagonal terms in equation (21) can be chosen in the following two ways:

1. $K_{v12} = C_{e12}$ and $K_{v21} = C_{e21}$: In that case the off-diagonal terms will become zero. (22a)
2. $K_{v12} = -C_{e21}$ and $K_{v21} = -C_{e12}$: In that case both the off-diagonal terms will become equal and their values will be $-(C_{e12}+C_{e21})$. (22b)

Using equation (22a), it will be possible to write:

$$([K_v] - [C_e]) = \alpha_1 [M_e] + \alpha_2([K_p] - [G_e]) \quad (23)$$

where α_1 and α_2 are some arbitrary constants. Thus, the second term in equation (19) will become $\begin{bmatrix} \alpha_1 + \alpha_2\omega_1^2 & 0 \\ 0 & \alpha_1 + \alpha_2\omega_2^2 \end{bmatrix}$. This may be written as: $\begin{bmatrix} 2\xi_1\omega_1 & 0 \\ 0 & 2\xi_2\omega_2 \end{bmatrix}$ where ξ_1 and ξ_2 are modal damping ratios. The controller must exhibit non-oscillatory behavior to guarantee stability and for this, the minimum values of ξ_1 and ξ_2 should be 1 each. In that case, we obtain:

$$\alpha_1 = \frac{2\omega_1\omega_2}{\omega_1+\omega_2} \text{ and } \alpha_2 = \frac{2}{\omega_1+\omega_2} \quad (24)$$

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Now, the relationship between gains- K_v and K_p can be obtained as follows.

$$K_{v11} = \alpha_1 M_{e11} + \alpha_2 (K_{p11} - G_{e11}) + C_{e11}$$
$$K_{v12} = \alpha_1 M_{e12} + C_{e12}$$
$$K_{v21} = \alpha_1 M_{e21} + C_{e21}$$
$$K_{v22} = \alpha_1 M_{e22} + \alpha_2 (K_{p22} - G_{e22}) + C_{e22} \quad (25)$$

Similarly, equation (22b) can also be used to decouple the equation (9). This approach referred to as independent modal-space control (IMSC) [41] has been applied for a robotic system in the present work.

IV. Results and Discussions

In this section, results based upon the control gains obtained using equations- (24) and (25) are presented. Based upon these results, a comparison of control effectiveness is done between Computed-Torque Control (CTC) ([1], [2], [42], [43], [44]) and Coupled-Error Dynamics (CED) approach. For this purpose, the serial robot (Fig. 1) is guided to follow a certain trajectory. The problem of formulation and optimization of trajectories is discussed by Lin et al. [45] while the control of manipulators using resolved-motion is discussed by Whitney [46] and Luh et al. [47]. The error equation for a 'computed-torque controller' is given as:

$$\{\ddot{\theta}_e\} + [K_v]\{\dot{\theta}_e\} + [K_p]\{\theta_e\} = \{\tau_d\} \quad (26)$$

Equation (26) is mostly used for 'independent joint control.' The gain matrices- [K_p] and [K_v] are diagonal matrices and {d} represents the vector of externally applied torque. A comparison of the equations (9) and (26) underlines the contribution of this work. The linearised versions of Coriolis, Gyroscopic and Gravity terms are now part of the control system matrices. Following relationship between K_v and K_p are used in CTC.

$$diag[K_{vj}] = 2\sqrt{diag[K_{pj}]} \quad (27)$$

The method of finding the recommended control gain depends upon the natural frequency of the manipulator system [42]. The physical parameters used for the manipulator (Fig. 1) are provided in Table 1.

Table 1: Physical parameters for Two-Link manipulator

Symbol	Physical quantity	Value
L_1	Length of link 1	0.5 m
L_2	Length of link 2	0.5 m
m_1	Mass of link 1	0.0312 kg
m_2	Mass of link 2	0.0312 kg
I_{h1}	Hub inertia at joint 1	8 x 10^{-5} kg-m^2
I_{h2}	Hub inertia at joint 2	8 x 10^{-5} kg-m^2
M_p	Mass of payload	0.2 kg

The error equation for 'coupled-error dynamics' is given by equation (9). The control problem requires that the end-effector of the robot must trace a straight line having equation: $y = 0.268x + 0.5$, in the X-Y plane (Fig. 2). For this, the joints of the robot must follow the desired Point-to-Point trajectories described by equation (28). Both the joints start from the initial orientation of 30º at 't = 0 second' and reach the final orientations at 't = t_f = 20 second'. The joints start from rest at 't = 0 second' and come to rest at 't = t_f = 20 second'.

$$\theta_{1d} = 30 - \left(\frac{150}{t_f^3}\right)t^3 + \left(\frac{225}{t_f^4}\right)t^4 - \left(\frac{90}{t_f^5}\right)t^5;$$

$$\theta_{2d} = 30 + \left(\frac{750}{t_f^3}\right)t^3 - \left(\frac{1125}{t_f^4}\right)t^4 + \left(\frac{450}{t_f^5}\right)t^5;$$

$$\dot{\theta}_{1d} = -\left(\frac{450}{t_f^3}\right)t^2 + \left(\frac{900}{t_f^4}\right)t^3 - \left(\frac{450}{t_f^5}\right)t^5;$$

$$\dot{\theta}_{2d} = \left(\frac{2250}{t_f^3}\right)t^2 - \left(\frac{4500}{t_f^4}\right)t^3 + \left(\frac{2250}{t_f^5}\right)t^5 \quad (28)$$

In equation (28), t_f represents the final value of time in which the joints reach their final orientations. The design conditions used for formulating these joint-space trajectories are provided in Table 2 below.

Table 2: Design conditions for the formulation of joint-space trajectories

	Joint 1		Joint 2	
	t = 0 s	t = t_f (20 s)	t = 0 s	t = t_f (20 s)
Joint angular rotation	30º	15º	30º	105º
Joint angular speed	0°/s	0°/s	0°/s	0°/s
Joint angular acceleration	0°/s^2	0°/s^2	0°/s^2	0°/s^2
Maximum Joint speed	-1.40625°/s (at t = 10 s)		7.03125°/s (at t = 10 s)	
Joint angle at maximum speed	22.5°		67.5°	

The angular rotations of the joints at 't = 0 sec' are found out using inverse kinematics at point P and point Q shown in Fig 2. The inverse kinematics relations for the planar Two-Link Rigid manipulator (Fig. 1) are given as follows:

$$\theta_2 = cos^{-1}\left(\frac{\left(\sqrt{x^2+y^2}\right)^2 - L_1^2 - L_2^2}{2L_1L_2}\right);\ \theta_1 = tan^{-1}\left(\frac{y}{x}\right) - tan^{-1}\left(\frac{L_2 \sin\theta_2}{L_1 + L_2 \cos\theta_2}\right) \quad (29)$$

Fig. 2 shows the path traced by the end-effector of Two-Link Rigid manipulator in X-Y plane.

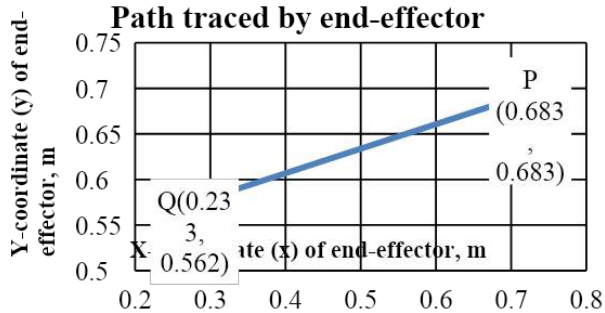

Fig. 2: Path traced by the end-effector of manipulator shown in Fig. 1

Using Table 2, the design parameters for the CED-based controller involving the coefficients- $[M_e]$, $[C_e]$, and $[G_e]$ provided in equation (9) are found out to be as follows.

$$M_e = \begin{bmatrix} 0.1238 + 0.0442\cos\theta_{2e} + 0.1068\sin\theta_{2e} & 0.0578 + 0.0221\cos\theta_{2e} + 0.0534\sin\theta_{2e} \\ 0.0578 + 0.0221\cos\theta_{2e} + 0.0534\sin\theta_{2e} & 0.0579 \end{bmatrix}$$

$$C_e = \begin{bmatrix} -0.0052\theta_{2e} + 0.0096 & 0.0116\theta_{2e} - 0.0281 \\ 0.0107\theta_{2e} - 0.0234 & -0.0019\theta_{2e} + 0.0045 \end{bmatrix};\ G_e = \begin{bmatrix} 0.1658 & 0.1156 \\ 0.1156 & 0.1156 \end{bmatrix} \quad (30)$$

In equation (30), θ_{2e} represents the joint error angle in Joint 2. The designer may check the accuracy required at the tip of the manipulator by selecting the value of θ_{2e}. Table 3 shows the control gains for the CED-based controller (based on equations- 24 and 25) and the CTC-based controller (based on equation (27)) for critically damped responses of the controllers.

Table 3: Control gains for CED-based controller and CTC-based controller for critically damped response for the Two-Link Rigid manipulator

CED-based controller (equations- 24 and 25)		CTC-based controller (equation 27)
$\theta_{2e} = 0$ radian	$\theta_{2e} = 0.1$ radian	
$K_p = \begin{bmatrix} 289 & 0.1156 \\ 0.1156 & 121 \end{bmatrix}$	$K_p = \begin{bmatrix} 289 & 0.1156 \\ 0.1156 & 121 \end{bmatrix}$	$K_p = \begin{bmatrix} 289 & 0 \\ 0 & 121 \end{bmatrix}$,
$K_v = \begin{bmatrix} 12.5539 & 3.8761 \\ 3.8809 & 4.6529 \end{bmatrix}$	$K_v = \begin{bmatrix} 12.8466 & 4.1178 \\ 4.1223 & 4.5648 \end{bmatrix}$	$K_v = \begin{bmatrix} 34 & 0 \\ 0 & 22 \end{bmatrix}$

Table 3 provides the values of K_p and K_v matrices for CED-based and CTC-based controllers. The values in derivative gain matrix K_v depend upon values in proportional gain matrix K_p and also the level of accuracy required in case of CED-based controller. This level of accuracy is described by angle θ_{2e}. On the other hand, in CTC-based controller, the values in K_v matrix depend upon the values in K_p matrix only. Once K_p is fixed, K_v also gets fixed. Thus, CED provides a facility to improve the transient response of the manipulator by changing the derivative gain K_v based upon the uncertainty θ_{2e} present within the system. A comparison between the performances of CED-based controller and CTC-based controller is made below. Figure 3 is obtained by using the K_p and K_v matrices as provided in the first column of Table 3 for CED-based controller and third column for CTC-based controller. It can be seen that the positional accuracy of the end-effector obtained in case of CED-based controller lies very close to that of the CTC-based controller.

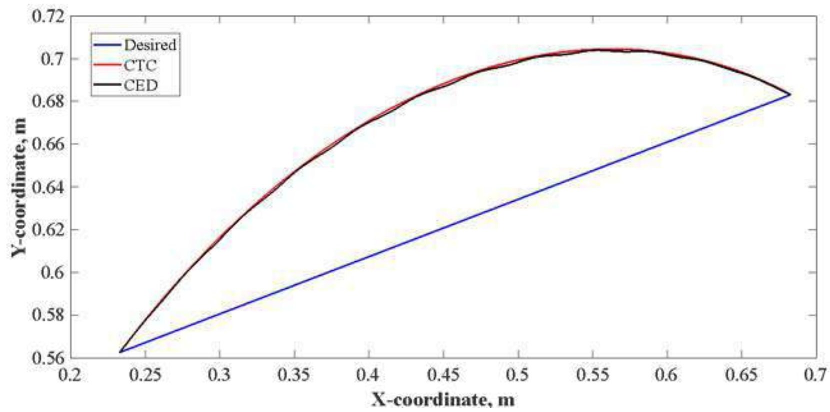

Fig. 3: Comparison of paths traced by end-effector of Two-Link Rigid robot in X-Y plane as obtained by CED and CTC (Table 3)

Figures- 3a and 3b above, show the comparison between paths traced by the end-effector of Two-Link Rigid manipulator using both CED and CTC approaches. The desired path is shown by straight lines in the figures. From the figure, it can be seen that the positional accuracy of CED- based controller is very close to that of a CTC except that there are few fluctuations. A comparison between the control torques provided by CED and CTC is also done. Fig. 4(a) and Fig. 4(b) show the comparison between control torques provided by CED and CTC based controllers for the PD gains provided in Table 3 (column 1 and column 3).

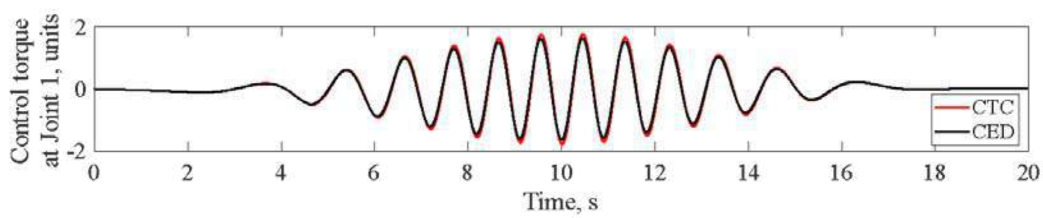

Fig. 4(a)

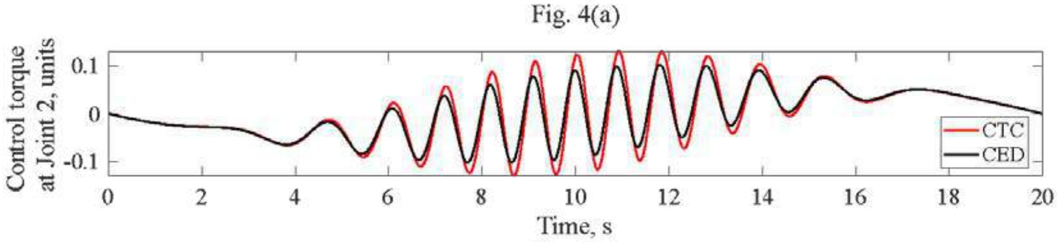

Fig. 4(b)

Fig. 4: Comparison between control torques provided by CED and CTC using control gains provided in columns 3 and 4 in Table 3 for the two-link rigid manipulator

From Fig. 4(a) and Fig. 4(b), it can be observed that the control torque at Joint 1 is approximately same for the CED controller and CTC. For Joint 2, the control torque provided by CED controller is slightly lower than the CTC. The results show that the performance of CED-based controller is comparable to that of the CTC and hence it can be used for trajectory control of robotic manipulators with a great level of accuracy and precision. Now, effect of external disturbance on the performance of the proposed controller will be discussed. For this, a unit step load input is applied at both the joints and joint errors obtained using CED-based controller and CTC are compared with each other. It is found that when only PD gains are used, CTC has a better steady state response than the CED. In the presence of external disturbance, the joint errors in the CED-based controller are higher than that of CTC. It is due to the nature of dynamics. In CED, the joint error of one joint affects the accuracy of the other joint (equation 9) because in a serial robotic manipulator all the links are connected with each other and hence motion of each joint is affected by the motion of another joint. Since, this coupling effect is not there in the dynamics of CTC (equation 26), the joint errors are less. In order to reduce the joint errors in CED-based controller, integral gains are used. The method of calculating the integral gains are provided by equation (31) given below.

$$K_{Ii} = K_{pi} \times K_{vi} \tag{31}$$

In equation (31), K_{Ii}, K_{pi} and K_{vi} are the integral gain, proportional gain and derivative gain respectively for link i. Fig. 5 shows the joint errors under the influence of unit step load applied at both the joints obtained for CED-based controller and CTC when PID gains are used.

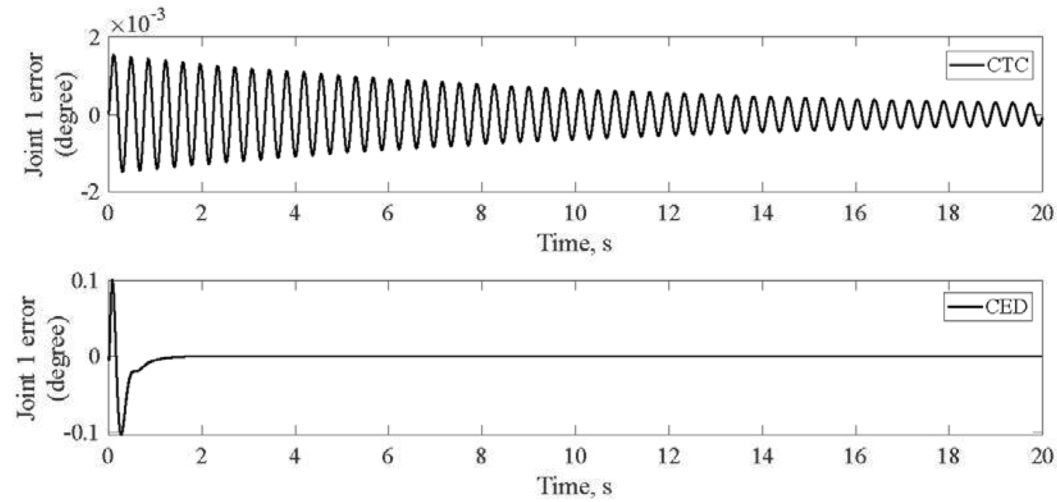

Fig. 5(a)

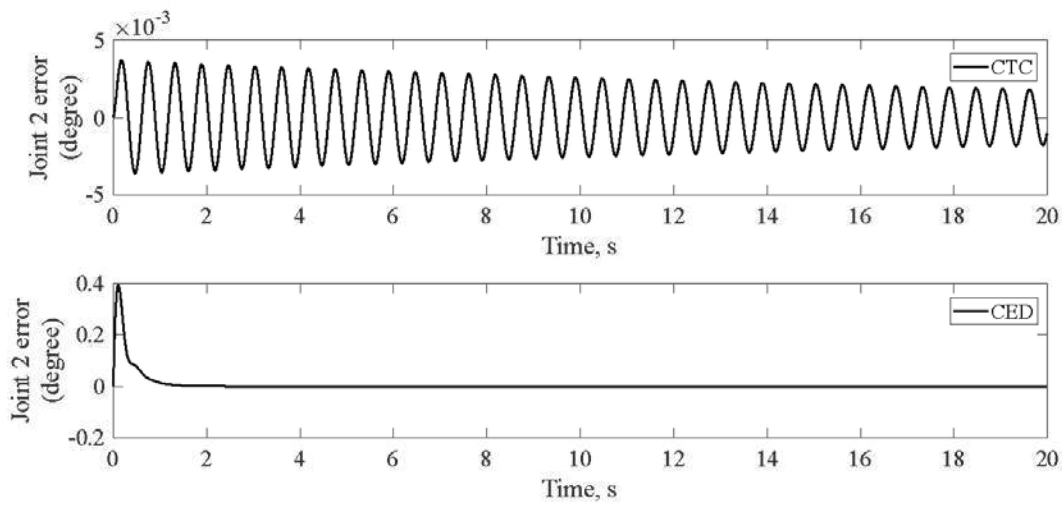

Fig. 5(b)

Fig. 5: Joint errors using PID gains under unit step disturbance for CED- based controller and CTC. (a) Joint 1 error, (b) Joint 2 error

From Fig. 5 it can be seen that due to introduction of integral gains, the joint errors are reduced to zero for the CED-based controller. For CTC also, the joint errors are significantly low but there are transients which decay with time. The only drawback with CED controller is that there is a high overshoot at the beginning. The control scheme based upon CED can be represented as shown below in Fig. 6.

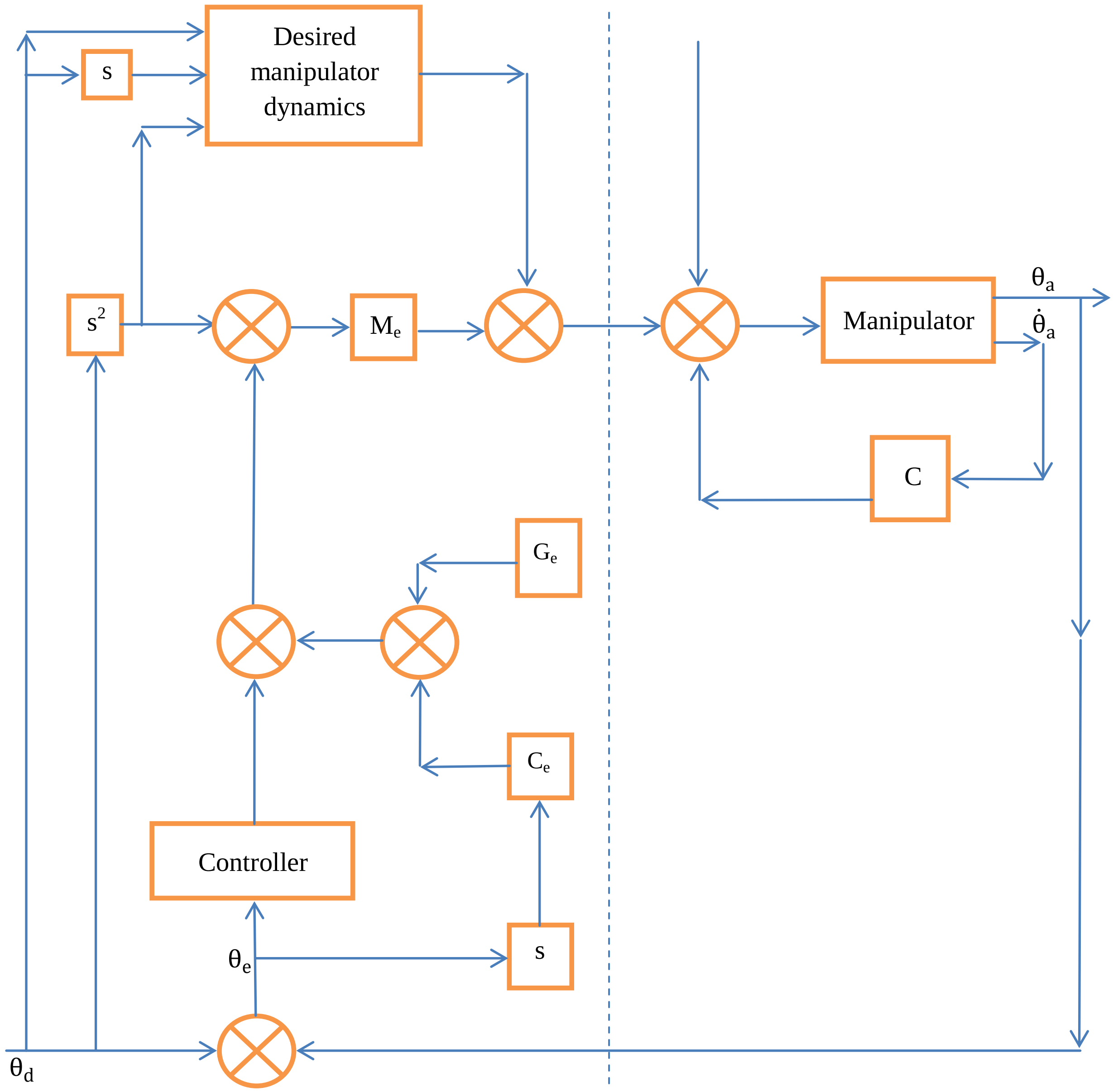

Fig. 6: Control scheme based upon Coupled-Error Dynamics (C = joint viscous damping)

The control scheme shown in Fig. 6 has two portions: Servo-based portion and Model-based portion. The servo-based portion consists of the required controller that minimizes the joint errors for the manipulator. The manipulator forms the model-based portion. It is to be noted that the terms C_e and G_e used here correspond to a representative value of θ_d and are not actively changed.

V. Effect of Link Flexibility on Controller Performance

In this section, the effect of link flexibility on performance of the proposed controller is discussed. For this, the mathematical model of the two-link flexible manipulator [48] is developed. Fig. 7 shows a two-link flexible manipulator undergoing both rigid and flexible motions.

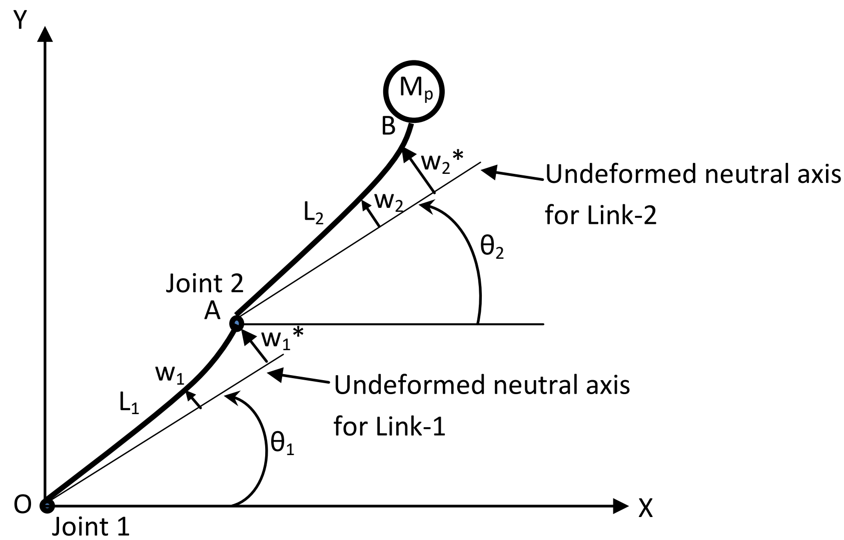

Fig. 7: Two Link Flexible manipulator

Fig. 7 shows a two-link flexible manipulator undergoing small elastic deformations. The flexible links have lengths- L_1 and L_2. In the figure, $\boldsymbol{\theta_1}$ and $\boldsymbol{\theta_2}$ represent the rigid rotations, w_1 and w_2 represent the small flexural deformations of the flexible links and w_1* and w_2* represent the small flexural deformations at the end points of the links respectively. The governing equations of motion can be obtained by using Lagrangian dynamics. A detailed formulation is provided by Mishra et al. [50]. The expressions for joint torques can be represented as follows.

$$\tau_1(t) = M_{11}\ddot{\theta}_1 + M_{12}\ddot{\theta}_2 + M_{13}\ddot{w}_1 + M_{14}\ddot{w}_2 + M_{15}\ddot{w}_1^* + M_{16}\ddot{w}_2^* + N_1 + G_1 + C_{11}\dot{\theta}_1 + C_{12}\dot{\theta}_2 + C_{15}\dot{w}_1^* + C_{16}\dot{w}_2^* + K_{15}w_1^* + K_1^{\#} \tag{32a}$$

$$\tau_2(t) = M_{21}\ddot{\theta}_1 + M_{22}\ddot{\theta}_2 + M_{23}\ddot{w}_1 + M_{24}\ddot{w}_2 + M_{25}\ddot{w}_1^* + M_{26}\ddot{w}_2^* + N_2 + G_2 + C_{21}\dot{\theta}_1 + C_{22}\dot{\theta}_2 + C_{25}\dot{w}_1^* + C_{26}\dot{w}_2^* + K_{25}w_1^* + K_2^{\#} \tag{32b}$$

In equation- (32), the terms M, N, G, C, K and $K^{\#}$ represent the inertia, centrifugal/Coriolis, gravity, gyroscopic/damping, stiffness and miscellaneous terms respectively. These expressions are derived after considering the bending angles at point A and point B (Fig. 7) as negligible. This is possible when the links have high flexural rigidity. The terms in equation (32) may be classified into rigid components and flexible components as follows.

$$\tau_1(t) = \tau_{1\_rigid} + \tau_{1\_flexible} \tag{33a}$$

$$\tau_2(t) = \tau_{2\_rigid} + \tau_{2\_flexible} \tag{33b}$$

In equations- (32) and (33), the rigid components of joint torques (1_rigid and 2_rigid) are same as given in equation (1) provided the joint dampings (C_{11}, C_{12}, C_{21} and C_{22}) are negligible. Rest other terms are considered under the category of flexible component of the joint torques (1_flexible and 2_flexible). In the proposed controller, the flexible components of joint torques act as the source of disturbance. The effect of link flexibility on the performances of the controllers in terms of end-effector position is shown in Fig. 8. The physical parameters of the flexible manipulator are same as for the rigid manipulator (Table 1) except the fact the values of flexural stiffness EI is taken as 1 Nm^2 for both the links.

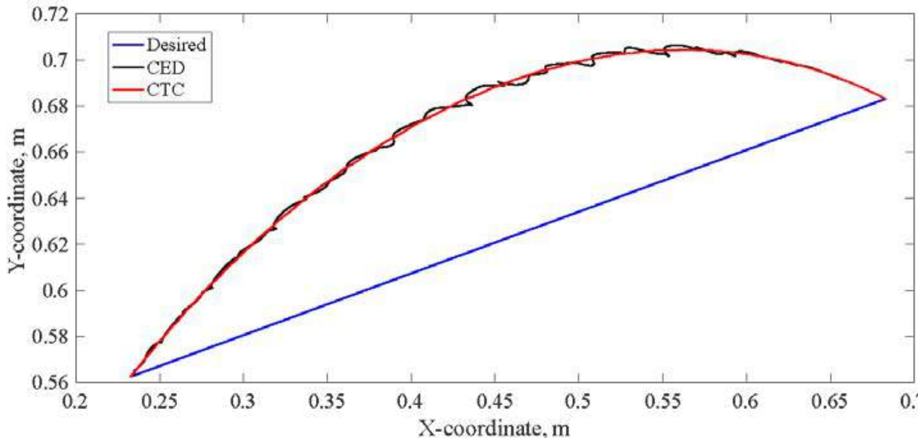

Fig. 8: Comparison of paths traced by end-effector of Two-Link Flexible robot in X-Y plane as obtained by CED and CTC

From Fig. 8, it can be seen that due to the presence of *flexibility* in the *links*, the positional accuracy obtained by CED-based controller gets decreased than as shown in Fig. 3. There is only slight decrease in accuracy of the CTC-based controller when compared with Fig. 3. But, comparatively high values of control gains are used. The values of control gains used for the *flexible* manipulator are provided below in Table 4.

Table 4: Control gains for CED-based controller and CTC-based controller for critically damped response for the Two-Link Flexible manipulator

CED-based controller (equations- 24 and 25); ($\theta_{2e} = 0$ radian)	CTC-based controller (equation 27)
$K_p = \begin{bmatrix} 324 & 0.1156 \\ 0.1156 & 144 \end{bmatrix}$	$K_p = \begin{bmatrix} 324 & 0 \\ 0 & 144 \end{bmatrix}$
$K_v = \begin{bmatrix} 13.3406 & 4.1638 \\ 4.1685 & 5.0547 \end{bmatrix}$	$K_v = \begin{bmatrix} 36 & 0 \\ 0 & 24 \end{bmatrix}$
$K_i = K_p \times K_v$	$K_i = K_p \times K_v$

The positional inaccuracy as observed in the response obtained by using CED-based controller is due to the effect of coupling between the joints of the flexible manipulator. The positional accuracy can be increased by increasing the values of control gains. Fig. 9 shows the comparison between the control torque requirements at the joints of the two-link flexible manipulator due to the CED and CTC-based controllers. It can be seen that the CED-based controller provides lesser control torques at the joints than the CTC-based controller. This is one reason why one obtains the good positional accuracy (Fig. 8) in case of CTC. But it is remarkable that the CED achieves the positional accuracy close to that of the CTC (Fig. 8) even at low values of control torques (Fig. 9).

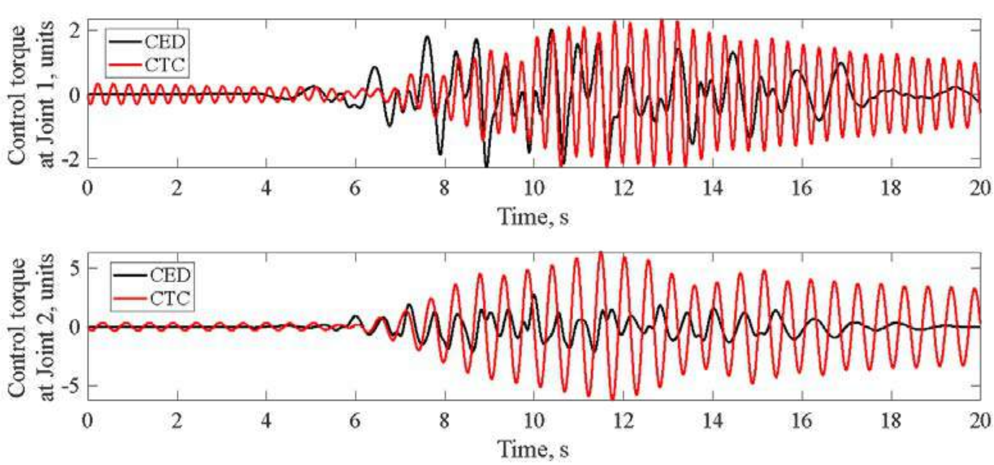

Fig. 9: Comparison between control torques provided by CED and CTC using control gains provided in Table 4 for the two-link flexible manipulator

VI. Conclusions and Future Directions

In the present paper, the dynamics of a two-link rigid robot is reformulated as a coupled-error dynamics problem. This new equation retains the essence of original equation; it is non-linear and involves coupling between joint variables and also exhibits time and configuration dependent inertia. The centrifugal and Coriolis' torques vectors are expressed as linear function of joint error velocity $\{\dot{\theta}_e\}$. Similarly the gravity terms are expressed as linear funcitons of joint error in an approximate manner. An approach for deciding the control gains based upon modal parameters is presented. This helps in obtaining good performance from the controller even at low values of control gains. This results in low control torque requirement with improved positional accuracy of the robot simultaneously. On the other hand, it is advisable to use CTC when joint inertias are negligible [48] and when all the dynamic parameters of the given system are known with certainty [49]. The results presented in this paper are based upon simulation and include the effects of both the link and joint inertias and external disturbance. It is shown that the proposed controller based upon coupled-error dynamics scheme yields promising results in the presence of both internal disturbance in the form of link flexibility and external disturbance. In future, it is required to perform experiments and validate the results. Furthermore, the performance of the controller is shown by using polynomial trajectories. It is required to check the effect of various other types of trajectories on the performance of CED-based controller.

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Competing Interests

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Acknowledgments

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Manuscript Style Instruction (Optional)

- Microsoft Word Document Setting Instructions.
- Font type of all text should be Swis721 Lt BT.
- Page size: 8.27" x 11'", left margin: 0.65, right margin: 0.65, bottom margin: 0.75.
- Paper title should be in one column of font size 24.
- Author name in font size of 11 in one column.
- Abstract: font size 9 with the word "Abstract" in bold italics.
- Main text: font size 10 with two justified columns.
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- First character must be three lines drop-capped.
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- Large images must be in one column.
- The names of first main headings (Heading 1) must be in Roman font, capital letters, and font size of 10.
- The names of second main headings (Heading 2) must not include numbers and must be in italics with a font size of 10.

Structure and Format of Manuscript

The recommended size of an original research paper is under 15,000 words and review papers under 7,000 words. Research articles should be less than 10,000 words. Research papers are usually longer than review papers. Review papers are reports of significant research (typically less than 7,000 words, including tables, figures, and references)

A research paper must include:

a) A title which should be relevant to the theme of the paper.
b) A summary, known as an abstract (less than 150 words), containing the major results and conclusions.
c) Up to 10 keywords that precisely identify the paper's subject, purpose, and focus.
d) An introduction, giving fundamental background objectives.
e) Resources and techniques with sufficient complete experimental details (wherever possible by reference) to permit repetition, sources of information must be given, and numerical methods must be specified by reference.
f) Results which should be presented concisely by well-designed tables and figures.
g) Suitable statistical data should also be given.
h) All data must have been gathered with attention to numerical detail in the planning stage.

Design has been recognized to be essential to experiments for a considerable time, and the editor has decided that any paper that appears not to have adequate numerical treatments of the data will be returned unrefereed.

i) Discussion should cover implications and consequences and not just recapitulate the results; conclusions should also be summarized.
j) There should be brief acknowledgments.
k) There ought to be references in the conventional format. Global Journals recommends APA format.

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The full postal address of any related author(s) must be specified.

Abstract

The abstract is the foundation of the research paper. It should be clear and concise and must contain the objective of the paper and inferences drawn. It is advised to not include big mathematical equations or complicated jargon.

Many researchers searching for information online will use search engines such as Google, Yahoo or others. By optimizing your paper for search engines, you will amplify the chance of someone finding it. In turn, this will make it more likely to be viewed and cited in further works. Global Journals has compiled these guidelines to facilitate you to maximize the web-friendliness of the most public part of your paper.

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A major lynchpin of research work for the writing of research papers is the keyword search, which one will employ to find both library and internet resources. Up to eleven keywords or very brief phrases have to be given to help data retrieval, mining, and indexing.

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One should start brainstorming lists of potential keywords before even beginning searching. Think about the most important concepts related to research work. Ask, "What words would a source have to include to be truly valuable in a research paper?" Then consider synonyms for the important words.

It may take the discovery of only one important paper to steer in the right keyword direction because, in most databases, the keywords under which a research paper is abstracted are listed with the paper.

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Numerical methods used should be transparent and, where appropriate, supported by references.

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Authors must list all the abbreviations used in the paper at the end of the paper or in a separate table before using them.

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Authors are advised to submit any mathematical equation using either MathJax, KaTeX, or LaTeX, or in a very high-quality image.

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Tables: Tables should be cautiously designed, uncrowned, and include only essential data. Each must have an Arabic number, e.g., Table 4, a self-explanatory caption, and be on a separate sheet. Authors must submit tables in an editable format and not as images. References to these tables (if any) must be mentioned accurately.

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Figures are supposed to be submitted as separate files. Always include a citation in the text for each figure using Arabic numbers, e.g., Fig. 4. Artwork must be submitted online in vector electronic form or by emailing it.

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Although low-quality images are sufficient for review purposes, print publication requires high-quality images to prevent the final product being blurred or fuzzy. Submit (possibly by e-mail) EPS (line art) or TIFF (halftone/ photographs) files only. MS PowerPoint and Word Graphics are unsuitable for printed pictures. Avoid using pixel-oriented software. Scans (TIFF only) should have a resolution of at least 350 dpi (halftone) or 700 to 1100 dpi (line drawings). Please give the data for figures in black and white or submit a Color Work Agreement form. EPS files must be saved with fonts embedded (and with a TIFF preview, if possible).

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3. Ask your guides: If you are having any difficulty with your research, then do not hesitate to share your difficulty with your guide (if you have one). They will surely help you out and resolve your doubts. If you can't clarify what exactly you require for your work, then ask your supervisor to help you with an alternative. He or she might also provide you with a list of essential readings.

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7. Revise what you wrote: When you write anything, always read it, summarize it, and then finalize it.

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14. Arrangement of information: Each section of the main body should start with an opening sentence, and there should be a changeover at the end of the section. Give only valid and powerful arguments for your topic. You may also maintain your arguments with records.

15. Never start at the last minute: Always allow enough time for research work. Leaving everything to the last minute will degrade your paper and spoil your work.

16. Multitasking in research is not good: Doing several things at the same time is a bad habit in the case of research activity. Research is an area where everything has a particular time slot. Divide your research work into parts, and do a particular part in a particular time slot.

17. Never copy others' work: Never copy others' work and give it your name because if the evaluator has seen it anywhere, you will be in trouble. Take proper rest and food: No matter how many hours you spend on your research activity, if you are not taking care of your health, then all your efforts will have been in vain. For quality research, take proper rest and food.

18. Go to seminars: Attend seminars if the topic is relevant to your research area. Utilize all your resources.

19. Refresh your mind after intervals: Try to give your mind a rest by listening to soft music or sleeping in intervals. This will also improve your memory. Acquire colleagues: Always try to acquire colleagues. No matter how sharp you are, if you acquire colleagues, they can give you ideas which will be helpful to your research.

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22. Report concluded results: Use concluded results. From raw data, filter the results, and then conclude your studies based on measurements and observations taken. An appropriate number of decimal places should be used. Parenthetical remarks are prohibited here. Proofread carefully at the final stage. At the end, give an outline to your arguments. Spot perspectives of further study of the subject. Justify your conclusion at the bottom sufficiently, which will probably include examples.
23. Upon conclusion: Once you have concluded your research, the next most important step is to present your findings. Presentation is extremely important as it is the definite medium though which your research is going to be in print for the rest of the crowd. Care should be taken to categorize your thoughts well and present them in a logical and neat manner. A good quality research paper format is essential because it serves to highlight your research paper and bring to light all necessary aspects of your research.

Informal Guidelines of Research Paper Writing

Key points to remember:

- Submit all work in its final form.
- Write your paper in the form which is presented in the guidelines using the template.
- Please note the criteria peer reviewers will use for grading the final paper.

Final points:

One purpose of organizing a research paper is to let people interpret your efforts selectively. The journal requires the following sections, submitted in the order listed, with each section starting on a new page:

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The discussion section:

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An abstract is a brief, distinct paragraph summary of finished work or work in development. In a minute or less, a reviewer can be taught the foundation behind the study, common approaches to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Use comprehensive sentences, and do not sacrifice readability for brevity; you can maintain it succinctly by phrasing sentences so that they provide more than a lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study with the subsequent elements in any summary. Try to limit the initial two items to no more than one line each.

Reason for writing the article—theory, overall issue, purpose.

- Fundamental goal.
- To-the-point depiction of the research.
- Consequences, including definite statistics—if the consequences are quantitative in nature, account for this; results of any numerical analysis should be reported. Significant conclusions or questions that emerge from the research.

Approach:

- o Single section and succinct.
- o An outline of the job done is always written in past tense.
- o Concentrate on shortening results—limit background information to a verdict or two.
- o Exact spelling, clarity of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else.

Introduction:

The introduction should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable of comprehending and calculating the purpose of your study without having to refer to other works. The basis for the study should be offered. Give the most important references, but avoid making a comprehensive appraisal of the topic. Describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will give no attention to your results. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here.

The following approach can create a valuable beginning:

- o Explain the value (significance) of the study.
- o Defend the model—why did you employ this particular system or method? What is its compensation? Remark upon its appropriateness from an abstract point of view as well as pointing out sensible reasons for using it.
- o Present a justification. State your particular theory(-ies) or aim(s), and describe the logic that led you to choose them.
- o Briefly explain the study's tentative purpose and how it meets the declared objectives.

Approach:

Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done. Sort out your thoughts; manufacture one key point for every section. If you make the four points listed above, you will need at least four paragraphs. Present surrounding information only when it is necessary to support a situation. The reviewer does not desire to read everything you know about a topic. Shape the theory specifically—do not take a broad view.

As always, give awareness to spelling, simplicity, and correctness of sentences and phrases.

Procedures (methods and materials):

This part is supposed to be the easiest to carve if you have good skills. A soundly written procedures segment allows a capable scientist to replicate your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order, but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt to give the least amount of information that would permit another capable scientist to replicate your outcome, but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section.

When a technique is used that has been well-described in another section, mention the specific item describing the way, but draw the basic principle while stating the situation. The purpose is to show all particular resources and broad procedures so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step-by-step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

Materials may be reported in part of a section or else they may be recognized along with your measures.

Methods:

- Report the method and not the particulars of each process that engaged the same methodology.
- Describe the method entirely.
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures.
- Simplify—detail how procedures were completed, not how they were performed on a particular day.
- If well-known procedures were used, account for the procedure by name, possibly with a reference, and that's all.

Approach:

It is embarrassing to use vigorous voice when documenting methods without using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result, when writing up the methods, most authors use third person passive voice.

Use standard style in this and every other part of the paper—avoid familiar lists, and use full sentences.

What to keep away from:

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings—save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part as entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Use statistics and tables, if suitable, to present consequences most efficiently.

You must clearly differentiate material which would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matters should not be submitted at all except if requested by the instructor.

Content:

- Sum up your conclusions in text and demonstrate them, if suitable, with figures and tables.
- In the manuscript, explain each of your consequences, and point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation of an exacting study.
- Explain results of control experiments and give remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or manuscript.

What to stay away from:

- Do not discuss or infer your outcome, report surrounding information, or try to explain anything.
- Do not include raw data or intermediate calculations in a research manuscript.
- Do not present similar data more than once.
- A manuscript should complement any figures or tables, not duplicate information.
- Never confuse figures with tables—there is a difference.

Approach:

As always, use past tense when you submit your results, and put the whole thing in a reasonable order.

Put figures and tables, appropriately numbered, in order at the end of the report.

If you desire, you may place your figures and tables properly within the text of your results section.

Figures and tables:

If you put figures and tables at the end of some details, make certain that they are visibly distinguished from any attached appendix materials, such as raw facts. Whatever the position, each table must be titled, numbered one after the other, and include a heading. All figures and tables must be divided from the text.

Discussion:

The discussion is expected to be the trickiest segment to write. A lot of papers submitted to the journal are discarded based on problems with the discussion. There is no rule for how long an argument should be.

Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implications of the study. The purpose here is to offer an understanding of your results and support all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of results should be fully described.

Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact, you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved the prospect, and let it drop at that. Make a decision as to whether each premise is supported or discarded or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."

Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work.

- You may propose future guidelines, such as how an experiment might be personalized to accomplish a new idea.
- Give details of all of your remarks as much as possible, focusing on mechanisms.
- Make a decision as to whether the tentative design sufficiently addressed the theory and whether or not it was correctly restricted. Try to present substitute explanations if they are sensible alternatives.
- One piece of research will not counter an overall question, so maintain the large picture in mind. Where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

When you refer to information, differentiate data generated by your own studies from other available information. Present work done by specific persons (including you) in past tense.

Describe generally acknowledged facts and main beliefs in present tense.

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Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

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