Modeling and Analysis of the Dynamic Performance of a Robot Manipulator driving by an Electrical Actuator Using Bond Graph Methodology

Fatima Zahra Baghli*[,1], Larbi El bakkali[1]

[1] *Modeling and Simulation of Mechanical Systems Laboratory, Abdelmalek Essaadi University, Faculty of Sciences, BP.2121, M'hannech, 93002, Tetuan, Morocco*

*Corresponding author: Tel.: +212644989050, Fax: +212539994500, E-mail address: baghli.fatimazahra@gmail.com

***Abstract*-- In this present paper we propose a new approach for modeling a rigid multibody system based on Bond Graph methodology. The proposed method based on the transfer of energy between system components and on the description of the vector velocity relation of a moving point in a rotating system.**

Our mechatronic system is a double freedom robot manipulator driving by an electric actuator, can be efficiently modeled and solved by this multidisciplinary approach, this design of bond graph dynamic model of the arm manipulator derive information on structural controllability and observability. Also the advantages of bond graph modeling of the robot manipulator are notified.

***Index Term*-- Bond graph, Dynamic modeling, and Robot manipulator.**

1. Introduction

Research on the dynamic modeling and simulation of the arms manipulators has received increased attention since the last years due to their advantages, this system is a mechanical system multi-articulated, in which each articulation is driven individually by an electric actuator is the most robot used in industry. A good modeling of the specific manipulator needs an efficient method to describe all behaviors of system.

The Newton-Euler technique and Lagrange's technique are the most methods used for dynamic modeling; these techniques calculate a vector containing the force or torque required at each joint to attain a specified trajectory of joint positions, velocities and accelerations. The main disadvantages of the above modeling techniques are their complexity and lack of versatility [1].

The Bond Graph technique developed since the 1960's represent a powerful approach to modeling robotic manipulators and mechanisms [2-3].It is a graphical representation that depicts the interaction between elements of the system along with their cause and effect relationships. The use of Bond Graph to describe all behaviors of robotic manipulators can he developed based on kinematic relationships between the time rates of joint variables and the generalized Cartesian velocities (translational and angular velocities) [1].This efficient method can be used to obtain more information such as the power required to drive each joint actuator, or the power interaction at the interface with the environment, Such information can also be used to study the performances like stability, precision of the manipulator system.

In this work the study is extended to a highly non linear, multiple inputs multiple outputs (MIMO) system, this study is illustrated by the two arms manipulator. The aim of this work is to describe all behaviors of our system by using bond graphs.

The reminder paper was structured as follow: the Bond graph technique for modeling a mechanical and electrical system has been presented in second part of this paper, in the third part of this paper the systematic procedure to derive a Bond Graph is detailed, The equations of motion are derived from Bond graph model with the criteria of controller such as controllability and observability are presented in the last part of this paper and finally conclusion was given.

2. Bond Graph of Mechanical and Electrical System

2.1 Bonds

The basic element of bond graph is the energy bond (Fig.1) , in this method, power consists of two variables which are known as generalized effort generalized flow denoted by **e** and **f** respectively; these two variables are necessary and sufficient to describe the energetic transfers inside the system. The physical meaning of the effort and flow variables depends upon the physical domain the bond represents. For example, in the electrical domain the effort variable is voltage and the flow variable is current. A unidirectional semi headed arrow shows this energy interchange (the arrow on the bond denotes the direction of positive energy flow).

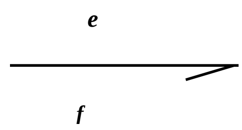

Fig.1. Energy bond with effort and flow

Table I gives examples of the effort and flow variables for mechanical and electrical domains.

Table I
Effort and Flow variables in some physical domains

Domain	Effort (e)	Flow (f)
Translation Mechanics	Force	Velocity
Rotational Mechanics	Torque	Angular velocity
Electricity	Voltage	Current

2.2 Components

There are four types of components labeled S, C, I, R, this elementary components are classified by their energetic behavior (energy dissipation, energy storage, etc.) and define how the effort and flow variables on the bond relate to each other. The Table 2 shows the elementary component of bond graph.

Table II
.Basic Bond Graph elements

Component	Symbol	Type of element	Example in translation mechanic domain	Example in rotational mechanic domain	Example in electric domain
Active elements	Se	Effort source	Force source	Torque source	Voltage source
	Sf	Flow source	Velocity source	Angular velocity source	Current source
Passive elements	R	Dissipation	Damper	Rot. Damper	Resistor
	I	Storage	Inertia	Rot. Inertia	Inductor
	C		Compliance	Rot. Compliance	Capacitor

2.3 Junctions

The Components are connected together using two types of junctions: a **0** or common effort junction and a **1** or common flow junction.

The 0 junction has the following properties: all bonds impinging upon it have the same effort variable and all flows on attached bonds sum to zero. Similarly the 1 junction has the properties: all bonds impinging upon it have the same flow variable and all efort on attached bonds sum to zero

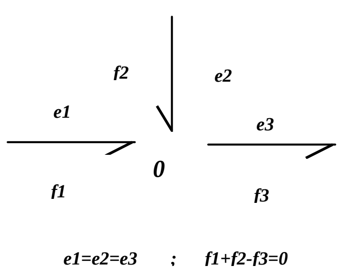

Fig. 2. 0-Junction

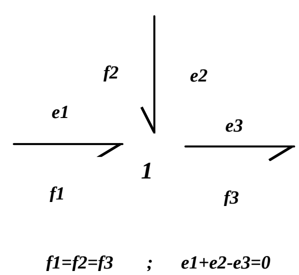

Fig. 3. 1-Junction

2.4 Connecting mechanical and electrical domains

To transfer between physical domains the ability to multiply must be included and bond graph provide two means of accomplishing this: the Transformer TF and the Gyrator Gy (TF or Gy are energy conserving).

Symbol	Mechanical domain	Electrical domain
TF	Lever	Transformer
Gy	Gyroscope	Motor Dc

2.4 Determining causality:

Bond graphs have a notion of causality, indicating which side of a bond determines the instantaneous effort and which determines the instantaneous flow. In formulating the dynamic equations that describe the system, causality defines, for each modeling element, which variable is dependent and which is independent.

The sources Se and Sf have fixed causality because there can

be only one output variable in relation to the source.
Storage elements C, I have “preferred causality”, the advantage is given to the integral causality over the differential one considering the fact that these elements are characterized by effort and flow accumulation which is manifested by the mechanism of integration in time, the rest of elements, as the element of dissipation R, have the so called “free causality’’ because they represent only static connection between the effort and the flow, The junction 1 has only one independent flow variable and only one bond with causal stroke which is not on the side of the element In the same way, 0 junction has only one independent effort variable, and only one bond with causal stroke towards the element of this connection. Therefore, Transformers and gyrators also have causal constraints. Table 3 shows the permitted causality permutations for components, junctions and transformers respectively.

Table III
Causality stroke and Assignments for bond graph

Causal form	Causal relation	Type
S_e S_f	$e = S_e$ $f = S_f$	Fixed Causality
R R	$f = \frac{e}{R}$ $e = R * f$	Resistor Conductivity
I I	$f = \frac{1}{I}\int e\,dt$ $e = I\frac{df}{dt}$	Integral Derived
C C	$e = \frac{1}{C}\int f\,dt$ $f = I\frac{de}{dt}$	Integral Derived
1 TF : m 2	$e_1 = m * e_2$; $f_2 = m * f_1$	Symmetric
1 TF :m 2	$e_2 = \frac{e_1}{m}$; $f_1 = \frac{f_2}{m}$	Symmetric
1 Gy : r 2	$e_1 = r * f_2$; $e_2 = r * f_1$	Antsymmetric
1 Gy : r 2	$f_2 = \frac{e_1}{r}$; $f_2 = \frac{e_2}{r}$	Antsymmetric
3 1 0 2	$e_2 = e_3 = e_1$ $f_1 = f_2 + f_3$	One effort is imposed on the junction 0
3 1 1 2	$f_2 = f_3 = f_1$ $e_1 = e_2 + e_3$	One flow is imposed on the junction 1

3. Description of the robot manipulator

In this section, geometric and kinematic models are used for modeling the behavior of a robot manipulator with 2DOF.
The parameters of the system are joint and operational positions, the first allows modifying its geometry and the second determines the position and the orientation of the end effector **M**. In Fig. 3 a schema is given of 2-link rigid arm in which each articulation is driven individually by an electric actuator:

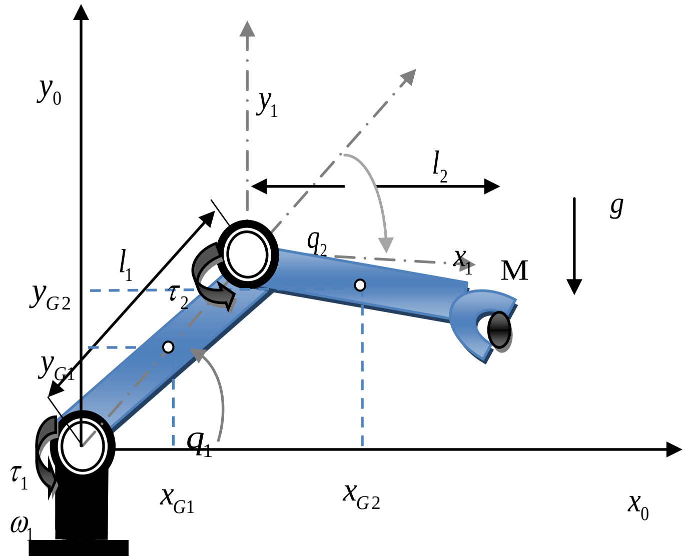

Fig. 3. Structure of manipulator robot of two degree of freedom

The meaning of the parameters of the prototype robot is shown in Table IV.

Table IV
Parameters

Parameters	Notation
Angular displacement of link 1	q_1
Angular displacement of link 2	q_2
Length of link1	l_1
Length of link2	l_2
Link 1 center of mass	l_{c1}
Link 2 center of mass	l_{c2}
Inertia link 1	I_1
Inertia link 2	I_2
Mass of link 1	m_1
Mass of link 2	m_2
Gravity acceleration	G

The positions and the velocities of the centers of mass of the two links are described by following equations:

$$x_{G1} = \frac{l_1}{2}\cos(q_1) \quad (1a)$$

$$y_{G1} = \frac{l_1}{2}\sin(q_1) \quad (1b)$$

$$vx_{G1} = -\omega_1 \frac{l_1}{2}\sin(q_1) \quad (2a)$$

$$vy_{G1} = \omega_1 \frac{l_1}{2}\cos(q_1) \quad (2b)$$

$$x_{G2} = l_1\cos(q_1) + \frac{l_2}{2}\cos(q_1+q_2) \quad (3a)$$

$$y_{G2} = l_1\sin(q_1) - \frac{l_2}{2}\sin(q_1+q_2) \quad (3b)$$

$$vx_{G2} = -\omega_1 l_1\sin(q_1) - \frac{l_2}{2}(\omega_1+\omega_2)\sin(q_1+q_2) \quad (4a)$$

$$vy_{G2} = \omega_1 l_1\cos(q_1) + \frac{l_2}{2}(\omega_1+\omega_2)\cos(q_1+q_2) \quad (4b)$$

Where: $\omega_i = \dot{q}_i$

The control input into the mechanical dynamics is a torque inputτ. However an electrical dynamic system from voltage to torque needs to be derived.

The following Fig.4 describe the circuitry within the DC motor system entrained joint robot arm (articulation), that consists of a resistor R, an inductor L, an external voltage source U, and a back EMF (E(t)) of the motor all placed in a series circuit.

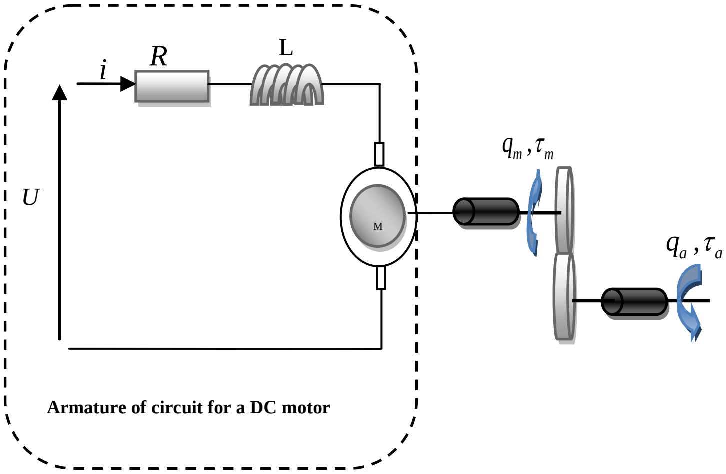

Fig. 4. schematic model of single joint robot arm driven by an armature controlled DC motor

The variable common to all the components of the armature circuit of DC motor is the current *i*, by using Kirchoff's voltage law, the external source voltage is equal to the sum of the individual voltages across each circuit component as shown in the following equation:

$$U(t) = Ri(t) + L\frac{di(t)}{dt} + E(t) \qquad (5)$$

The torque produced by a DC. motor is given by:

$$\tau_m = i(t)k_1 \qquad (6)$$

So, the torque applied to the rotational base in the robot manipulator is converted to the torque applied by the DC motor by means of a gear ratio k_2 given in the following equation:

$$\tau_a = k_2\tau_m \qquad (7)$$

4. Classical modeling of arm manipulator:

The dynamic equations of the robot are usually represented by the following Lagrange method

$$\tau = M(q)\ddot{q} + C(q,\dot{q}) + G(q) \qquad (8)$$

Where:

$q,\dot{q},\ddot{q} \in \mathbb{R}^n$ denotes the joint angle, the joint velocity and the joint acceleration, $M(q) \in \mathbb{R}^{n\times n}$ is the manipulator inertia matrix, $C(q,\dot{q}) \in \mathbb{R}^{n\times n}$ is the centrifugal and Coriolis force matrix, $G(q) \in \mathbb{R}^n$ is the gravitational force vector and $\tau(t)$ denotes the torque.

The robot dynamics is defined as:

$$M(q) = \begin{pmatrix} I_1 + I_2 + m_1 l_{c1}^2 + m_2\left(l_1^2 + l_{c2}^2\right) + 2m_2 l_1 l_{c2} c_2 & I_2 + m_2 l_{c2}^2 + m_2 l_1 l_2 c_2 \\ I_2 + m_2 l_{c2}^2 + m_2 l_1 l_2 c_2 & I_2 + m_2 l_{c2}^2 \end{pmatrix} \qquad 8a)$$

$$C(q,\dot{q}) = \begin{pmatrix} -m_2 l_1 l_{c2}\dot{q}_2 s_2 & -m_2 l_1 l_{c2}(\dot{q}_1 + \dot{q}_1)s_2 \\ m_2 l_1 l_2 \dot{q}_1^2 s_2 & 0 \end{pmatrix} \qquad (8b)$$

$$G(q) = \begin{pmatrix} (m_1 l_{c1} + m_2 l_1) g c_1 + m_2 g l_{c2} c_{12} \\ m_2 g l_{c2} c_{12} \end{pmatrix} \qquad (8c)$$

$$\tau = \begin{pmatrix} \tau_1 \\ \tau_2 \end{pmatrix} \qquad (8b)$$

Where:

$c_1 = \cos(q_1)$; $c_2 = \cos(q_2)$; $s_1 = \sin(q_1)$; $s_2 = \sin(q_2)$; $c_{12} = \cos(q_1 + q_2)$; $s_{12} = \sin(q_1 + q_2)$

5. Systematic procedure to derive a Bond graph model of system

The representation of the robot manipulator is developed by assembling bond graph represent of the different elements as shown in the word bond graph (Fig. 5)

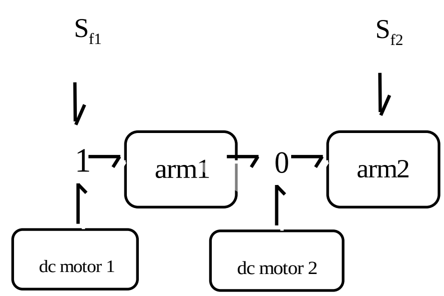

Fig. 5. Robot manipulator word bond graph with boundary conditions (S_{fi}) dc motor 1

5.1. Bond graph for a DC motor

The DC motor is simply modeled by a gyrator (GY) for the electromechanical conversion, with a proportional gain k_1.The bond graph of the armature will be constructed around a common flow (because the variable common to all the components is the current i). Connected to this junction will be a Source of voltage (Se), Inertia (I) corresponding to the armature inductance L and a Resistance (R) corresponding to the armature resistance R. The components to be added are the motor inertia Jm and the viscous friction b, to form the final version of the bond graph of Dc Motor shown in Fig. 6.

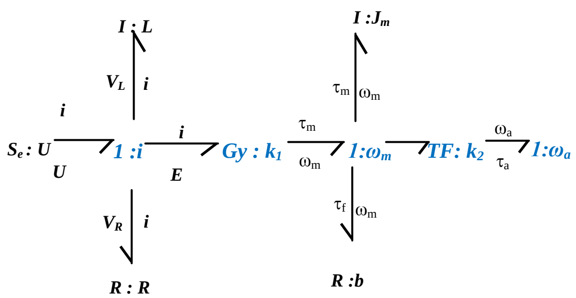

Fig. 6. Bond graph for DC motor

An integral causality is imposed when I and c components have the form as show in table. III
The causally complete Bond graph as shown in Fig. 7

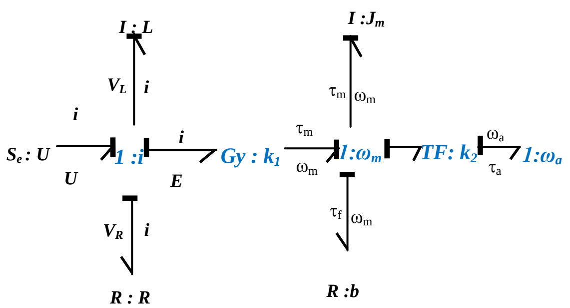

Fig. 7. Causally bond graph for DC motor

5.2. Bond graph for a rotating arm

The bond graph for the first arm is derived from expressions of the velocities of the center of mass Eq. (2a) and (2b).
The transformers are used to convert the angular velocity to a linear velocity and the dynamics can be introduced by adding I element to the arm as shown in Fig .8.

Where:

- $r_1 = l_{c1}\cos(q_1)$
- $r_2 = -l_{c1}\sin(q_1)$

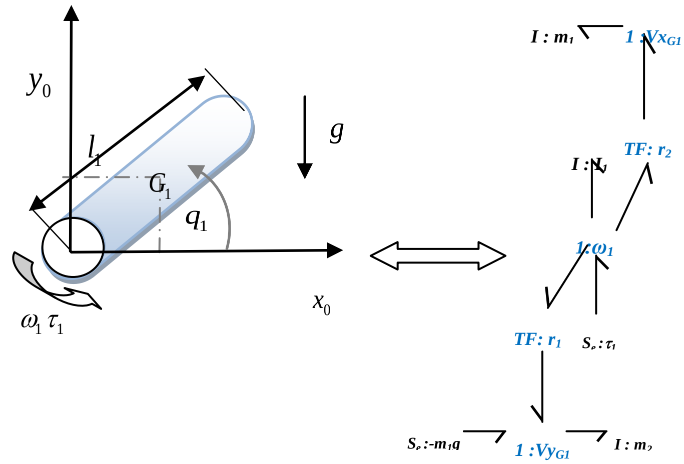

Fig. 8. Bond graph for rotating of the first arm

The base of the second arm is not fixed in space but depends on the velocity of its attachment point to the first arm, therefore, the development of the first and the second arm based on the expressions of the velocities of center mass of the second link Eq. (4a) and Eq. (4b).So, the complete bond graph of our system is shown in Fig 9.
Where:

- $r_3 = -l_{c2}\sin(q_2)$
- $r_4 = l_{c2}\cos(q_2)$

6. Structural Study

The bond graph causal model is considered as a structural model and we synthesis this last one by tracking into account control criteria (controllability and observability).
In terms of bond graphs, the notions of input reachable and output reachable are expressed as the existence of causal paths between dynamical elements (I, C in integral causality) and sources and detectors [9].

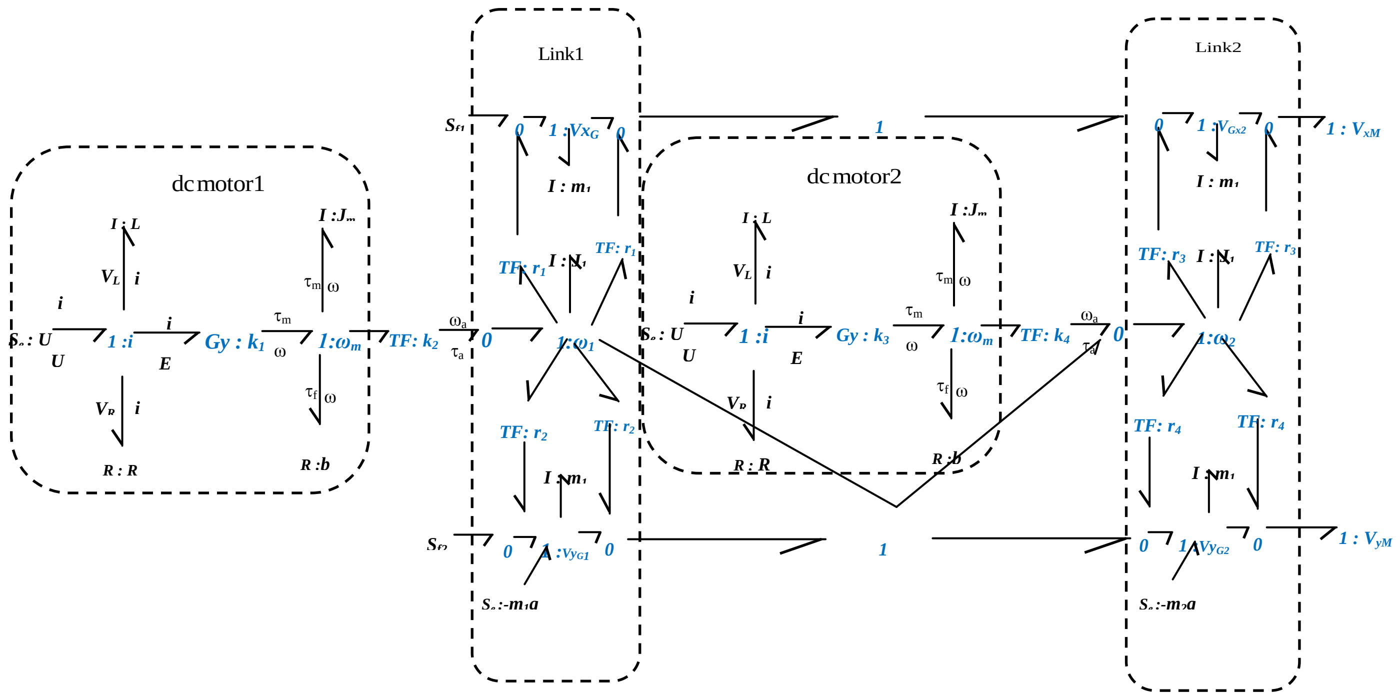

Fig. 9. Complete bond graph for the two link manipulator

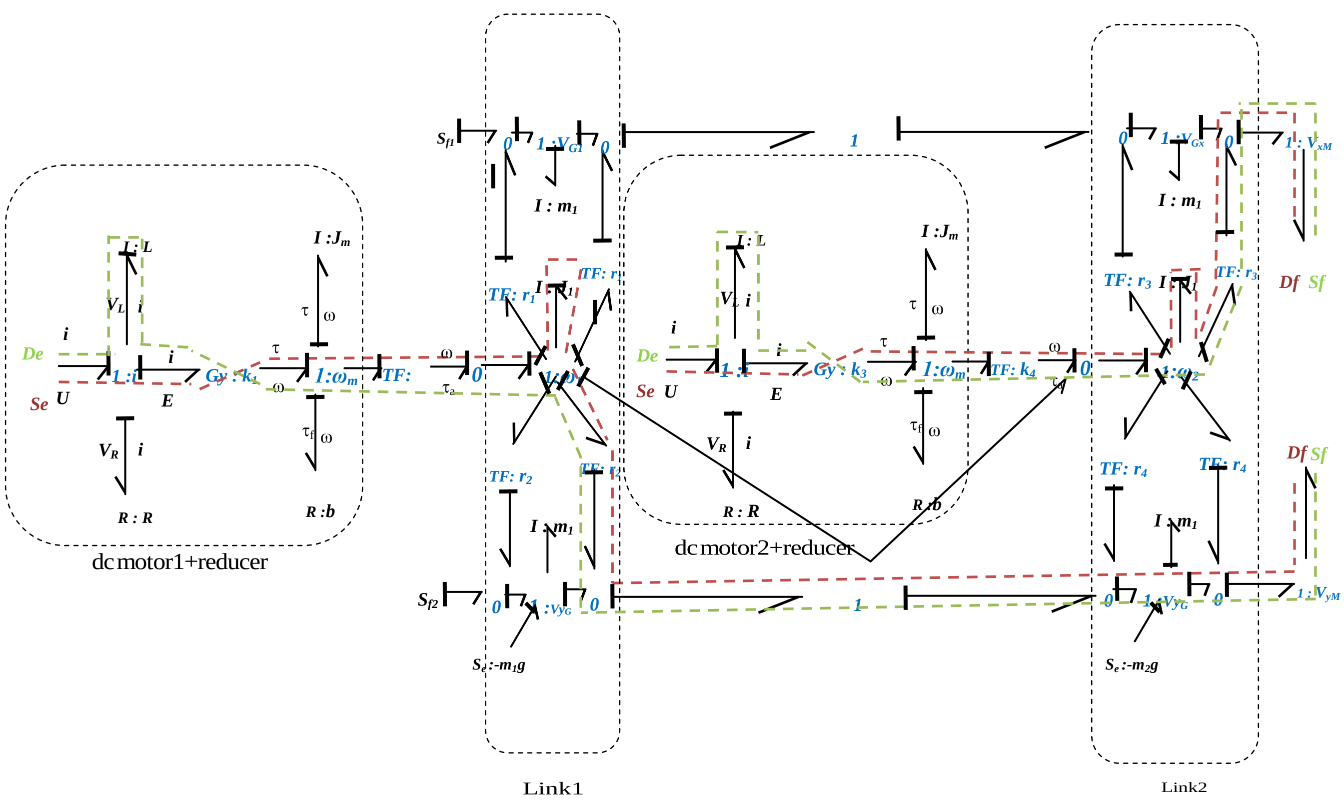

Fig. 10. Causally bond graph for the two link manipulator with causal roads connecting the input with the output (_ _ : controllability; _ _ : observability)

Theorem 1: A system is structurally state controllable if all dynamical elements (I, C) in integral causality are causally connected with a source (Se, Sf).

Theorem 2: A system is structurally state observable if all dynamical elements (I, C) in integral causality are causally connected with a detector (De, Df).

6.1. Consideration of controllability and observability

To put the model of our system in model BGD, it is necessary to make all storage elements in integral causality. Thus the criterion of controllability is verified with the two sources U1 and U2 as shown in Fig. 10.

To ensure the observability, it is necessary to verify the existence of a causal path between every Detectors and a dynamic element I and making all the dynamic element in complete causality, in our bond graph model there is a causal way between the dynamic element I in integral causality and the output so the system is structurally observable with the two detectoes De or Df as shown in Fig. 10.

After verifying structurally our model, we pass to the following step with consists in making a study behavioral of our system with the objective deriving the dynamic equations of our system from the bond graph model

7. Systematic procedure to derive the equation of motion from bond graph model

The simplified bond graph model of the robot manipulator can be represented as shown in Fig.11.

Where:

- $k_1 = -l_{c1}\sin(q_1)$
- $k_2 = l_{c1}\cos(q_1)$
- $k_3 = l_1\sin(q_1) - l_{c2}\sin(q_1+q_2)$
- $k_4 = -l_{c2}\sin(q_1+q_2)$
- $k_5 = l_{c2}\cos(q_1+q_2)$
- $k_6 = l_1\cos(q_1) + l_{c2}\cos(q_1+q_2)$

The junction equations and elements are illustrated in Tables V and Table VI

Table V

The junctions characteristic

Junction1	Junction 0	TF
$1:\begin{cases} e_1 - e_3 - e_4 - e_8 - e_{10} - e_{14} - e_{26} = 0 \\ f_1 = f_3 = f_4 = f_8 = f_{10} = f_{14} = f_{26} \end{cases}$	$0:\begin{cases} e_{25} = e_{26} = e_{27} \\ f_{26} - f_{27} + f_{25} = 0 \end{cases}$	$TF:k_1\begin{cases} e_3 = k_1 * e_{18} \\ f_{18} = k_1 * f_3 \end{cases}$
$1:\begin{cases} f_9 = f_{18} \\ e_{18} - e_9 = 0 \end{cases}$	$0:\begin{cases} e_{13} = e_{12} = e_{15} \\ f_{15} + f_{13} - f_{12} = 0 \end{cases}$	$TF:k_2\begin{cases} e_8 = k_2 * e_7 \\ f_{18} = k_1 * f_3 \end{cases}$
$1:\begin{cases} f_5 = f_6 = f_7 \\ e_6 + e_7 - e_5 = 0 \end{cases}$	$0:\begin{cases} e_{20} = e_{21} = e_{24} \\ f_{20} + f_{24} - f_{21} = 0 \end{cases}$	$TF:k_3\begin{cases} e_{14} = k_3 * e_{13} \\ f_{13} = k_3 * f_{14} \end{cases}$
$1:\begin{cases} f_{12} = f_{11} \\ e_{12} - e_{11} = 0 \end{cases}$	-	$TF:k_4\begin{cases} e_{16} = k_4 * e_{15} \\ f_{15} = k_4 * f_{15} \end{cases}$
$1:\begin{cases} e_2 - e_{16} - e_{17} - e_{19} - e_{25} = 0 \\ f_{25} = f_{16} = f_{17} = f_2 = f_{19} \end{cases}$	-	$TF:k_5\begin{cases} e_{19} = k_5 * e_{20} \\ f_{20} = k_5 * f_{19} \end{cases}$
$1:\begin{cases} e_{21} - e_{23} - e_{22} = 0 \\ f_{21} = f_{22} = f_{23} \end{cases}$		$TF:k_6\begin{cases} e_{10} = k_6 * e_{24} \\ f_{24} = k_6 * f_{10} \end{cases}$

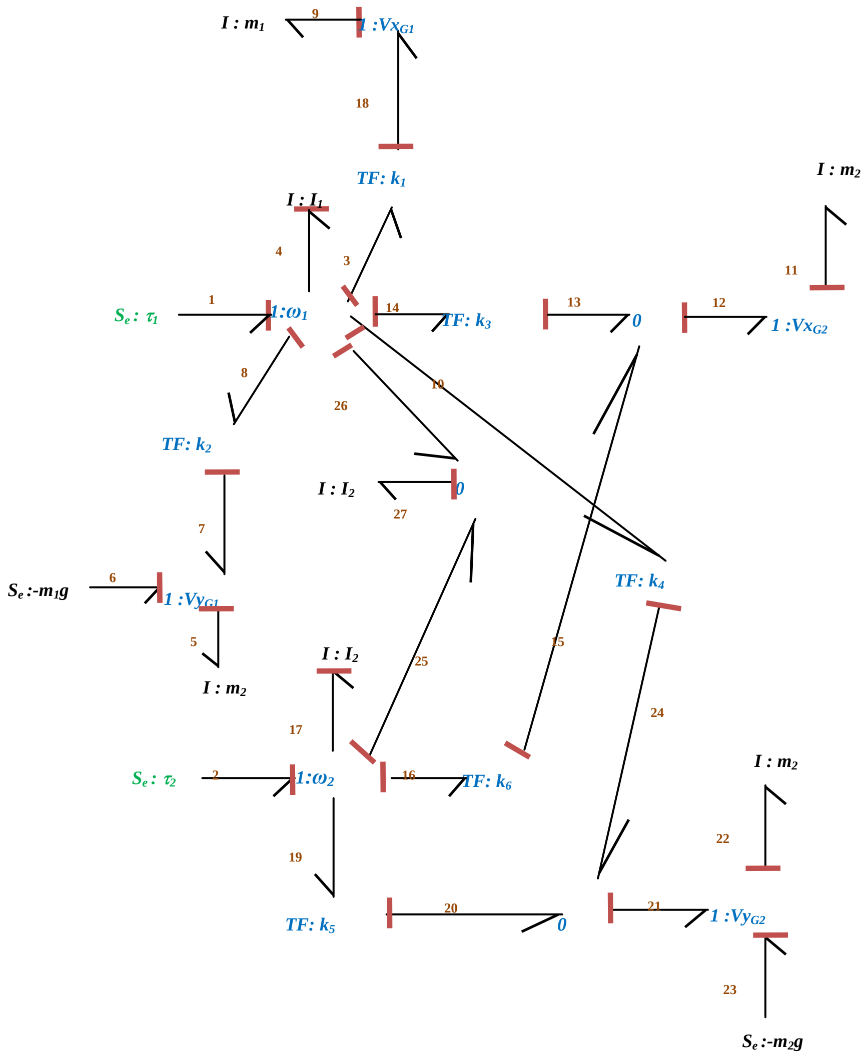

Fig. 11. Simplified Causally Bond Graph for the two link manipulator

Table VI

The equations of elements

Elements	
$I_1 : e_4 = I_1 \frac{df_4}{dt}$	$e_{11} = m_2 \frac{df_{11}}{dt}$
$m_1 : e_1 = m_1 \frac{df_1}{dt}$	$e_{22} = m_2 \frac{df_{22}}{dt}$
$m_5 : e_5 = m_1 \frac{df_5}{dt}$	$e_{23} = m_2 * g$
$e_6 = m_1 * g$	$e_{17} = I_2 \frac{df_{17}}{dt}$
$e_1 = \tau_1$; $e_2 = \tau_2$	$I_2 : e_{27} = I_{27} \frac{df_{27}}{dt}$

The torque applied to move link 1 can be obtained from the bond graph by the Eq. (9) and the external torque applied to move the second link by the Eq. (10).

$$\tau_1 = e_1 = e_3 + e_4 + e_8 + e_{10} + e_{14} + e_{26} \quad (9)$$

$$\tau_2 = e_2 = e_{16} + e_{17} + e_{19} + e_{25} \quad (10)$$

From the bond graph model and the precedent junction equations and elements we can formulate a set of manipulator robot differential equations in the following matrix form:

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} = \begin{bmatrix}M_{11}(q) & M_{12}(q)\\ M_{21}(q) & M_{22}(q)\end{bmatrix}\begin{bmatrix}\ddot{q}_1\\ \ddot{q}_2\end{bmatrix} + \begin{bmatrix}C_{11}(q,\dot{q}) & C_{12}(q,\dot{q})\\ C_{21}(q,\dot{q}) & C_{22}(q,\dot{q})\end{bmatrix}\begin{bmatrix}\dot{q}_1\\ \dot{q}_2\end{bmatrix} + \begin{bmatrix}G_1(q)\\ G_2(q)\end{bmatrix} \quad (11)$$

Where:

The elements of the inertia matrix M (q) in the terms of the parameters of the robot manipulator are given by:

$$M_{11}(q) = I_1 + I_2 + m_1 l_{c1}^2 + m_2 l_{c2}^2 + m_2 l_1^2 + 2m_2 l_1 l_{c2} c_2$$

$$M_{12}(q) = M_{21}(q) = I_2 + m_2 l_{c2}^2 + 2m_2 l_1 l_{c2} c_2$$

$$M_{22}(q) = 2I_2 + m_2 l_{c2}^2$$

The matrix elements $C_{ij}(q,\dot{q})(i,j=1,2)$ centrifugal and Coriolis force are:

$$C_{11}(q,\dot{q}) = -m_2 l_1 l_{c2} \dot{q}_2 s_2$$

$$C_{12}(q,\dot{q}) = -m_2 l_1 l_{c2} s_2 (\dot{q}_1 + \dot{q}_2)$$

$$C_{21}(q,\dot{q}) = m_2 l_1 l_{c2} \dot{q}_1 s_2$$

$$C_{22}(q,\dot{q}) = 0$$

Finally the elements of the vector of gravitational torques G (q) are given by:

$$G_1(q) = (m_1 + m_2) g l_{c1} c_1 + m_2 g l_{c2} c_{12}$$

$$G_2(q) = m_2 g l_{c2} c_{12}$$

The equations of external torque given by bond graph approach correspond to those obtained using Lagrange methods, as illustrated in Eq. (8).

This indicates that, the model developed capture the essential aspects of rigid body dynamics of the robot manipulator.

8. Controller Design

The general equation of the robot manipulator would be:

$$\frac{d}{dt}\begin{bmatrix}q\\ \dot{q}\end{bmatrix} = \begin{bmatrix}\dot{q}\\ M(q)^{-1}\left[\tau - C(q,\dot{q}) - G(q)\right]\end{bmatrix} \quad (12)$$

Robot control is the spine of robotics. It consists in studying how to make a robot manipulator do what it is desired to do automatically.

The dynamic model that characterizes the behavior of robot manipulators and obtained by bond graph is in general composed of nonlinear functions of the state variables (joint positions and velocities). This feature of the dynamic model might lead us to believe that given any controller.

The Fig.12 shows a block-diagram corresponding to a robot manipulator under feedforward control

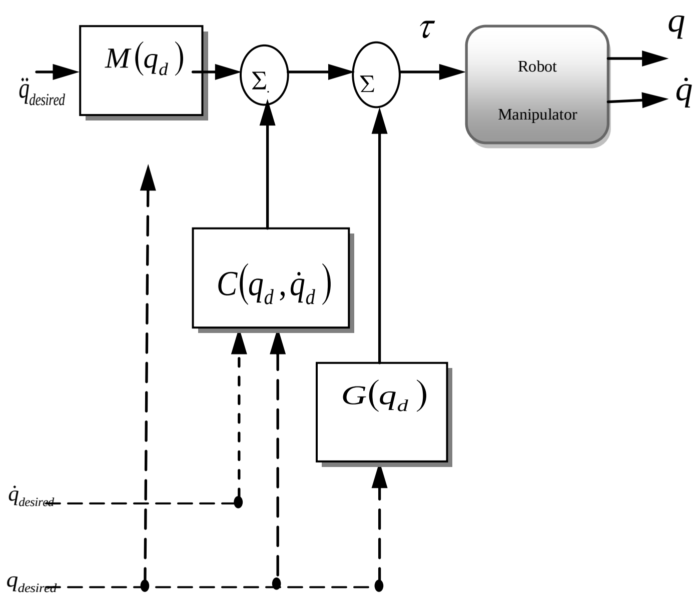

Fig. 12. Block-diagram of a robot manipulator

The state space equations Eq. (12) for this mechanical system have been derived. Solution these equations we can obtaine for example in MATLAB/Simulink.

9. SIMULATION

SISO control based on classical PID model is tested to sinus response trajectory [11]. This simulation applied to two degrees of freedom robot arm was implemented in Matlab/Simulink. The simulation results are illustrated by the following figures.

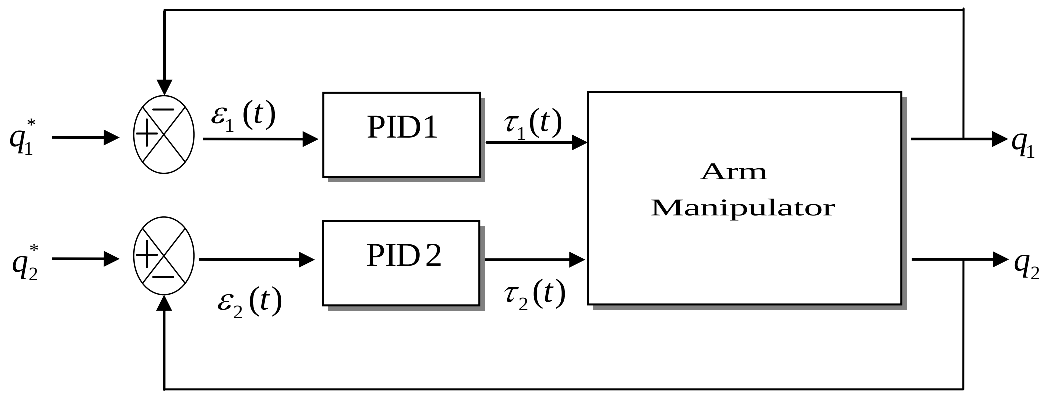

Fig. 13. Arm manipulator robot classical PID control

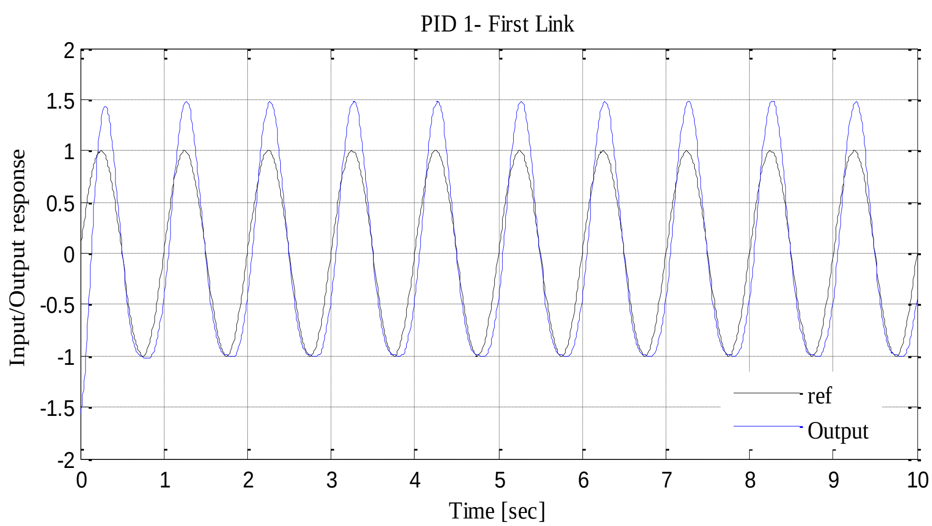

Fig. 14. PID (First link trajectory)

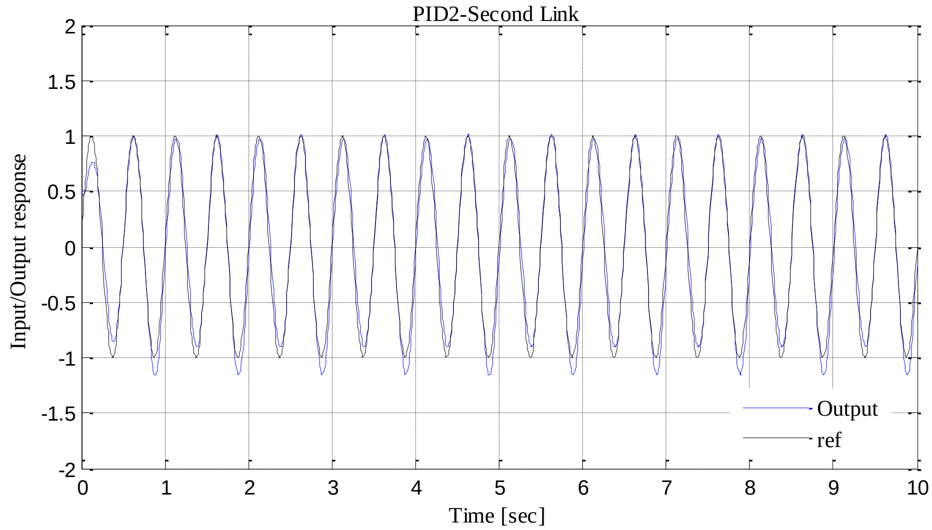

Fig. 15. PID (Second link trajectory)

10. Conclusions

In this paper, a new approach for modeling a robot manipulator is proposed, the proposed method is a concise and uniform language for the description of physical systems.

The modeling of our system using bond graph offers some useful advantages:

First, Ability to create bond graphs of large, complex system by connecting the bond graphs of simple sub-system.

Second, Graphical format is constructed through consideration of the kinematics of the robot manipulator.

Third, Dynamic equations of motion derived automatically from the causally complete bond graph of the two link manipulator.

Bond graph method combined with computer implementation is a very powerful tool for modeling and simulation of dynamic systems.

Acknowledgements

The authors would like to thank Oussama Khatib, Professor of Computer Science at Stanford University, California.

Abreviations

BGI : Bond graph in integral causality

BGD : Bond graph in derivative causality

De : Detector of effort

Df : Detector of flow

Sf : Flow source

Se : Effort source

EMF: Back electromotive force

References

[1] Anand Vaz, Harmesh Kansal and Ani1 Singla, Some Aspects in the Bond Graph Modelling of Robotic Manipulators: Angular Velocities from Symbolic Manipulation of Rotation Matrices, *IEEE 2003.*

[2] Darina Hroncováa, Patrik Šargaa, Alexander Gmiterkoa, Simulation of mechanical system with two degrees of freedom with Bond Graphs and MATLAB/Simulink, *Procedia Engineering 48 (2012) 223 – 232.*

[3] Wolfgang Borutzky, Bond Graph Methodology: Development and Analysis of Multi-disciplinary Dynamic System Models, *Springer 2010.*

[4] Soo-Jin Lee1, Pyung-Hun Chang, Modeling of a hydraulic excavator based on bond graph method and its parameter estimation, *Journal of Mechanical Science and Technology 26 (1) (2012) 195~204 .*

[5] Tore Bakka and Hamid Reza Karimi, Bond graph modeling and simulation of wind turbine systems, *Journal of Mechanical Science and Technology 27 (6) (2013) 1843~1852.*

[6] Dragan Antic, Biljana Vidojkovic and Miljana Mladenovic, An Introduction to Bond Graph Modelling of Dynamic Systems, *TELSIKS'99 13-1 5.October 1999, NiS, Yugoslavia*

[7] MA. Malik , A. Khurshid, Bond Graph Modeling and Simulation of` Mechatronic Systems, *Proceedings IEEE INMIC 2003.*

[8] C. Sueur, G.Dauphin-Tanguy Bond-graph Approach for Structural Analysis of MIMO Linear Systems, *Journal of the Frankhn Institute Pergamon Vol. 328, No. 1, pp. 55-70, 1991.*

[9] M.H. Toufighi, S.H. Sadati, F. Najafi Modeling and Analysis of a Mechatronic Actuator System by Using Bond Graph Methodology *IEEE. January 13, 2007.*

[10] Fatima Zahra Baghli, Larbi El bakkali, Yassine Lakhal, Abdelfatah Nasri, Brahim Gasbaoui, «The efficiency of the inference system knowledge strategy for the position control of a robot manipulator with two degree of freedom», *International Journal of Research in Engineering and Technology, Volume: 02 Issue: 07 Jul-2013.*

[11] Fatima Zahra Baghli, Larbi El Bakkali,Yassine Lakhal,Abdelfatah Nasri, Brahim Gasbaoui, "Arm manipulator position Control based on Multi-Input Multi-Output PID Strategy", *Journal of Automation, Mobile Robotics & Intelligent Systems , volume 8, N° 2, 2014.*