OPEN ACCESS
The Journal of Engineering and Exact Sciences – jCEC, Vol. 09 N. 04 (2023)
journal homepage: https://periodicos.ufv.br/jcec
eISSN: 2527-1075
ISSN: 2446-9416

Bond Graph-Based Modelling and Control of Electromagnetic Levitation System Using Firefly Optimization

Article Info:
Article history: Received 2023-02-02 / Accepted 2023-05-18 / Available online 2023-05-25
doi: 10.18540/jcecvl9iss4pp15867-01e

Ismail Dif
ORCID: https://orcid.org/0000-0002-7153-2480
Applied Automation and Industrial Diagnostics Laboratory (LAADI), Faculty of Science and Technology University of Ziane Achour of Djelfa, 17000, Algeria
E-mail: i.dif@univ-djelfa.dz
Naas Dif
ORCID: https://orcid.org/0000-0001-9474-6775
Saad Dahleb University Blida, LABSET Laboratory, Algeria
E-mail: naasdif@gmail.com
Khier Benmahammed
Intelligent Systems Laboratory (LSI), Department of Electronics, Faculty of Technology, Ferhat Abbas Setif1 University, Algeria
E-mail: khierben@yahoo.com

Abstract
This paper focuses on the modelling and control of an electromagnetic suspension using the bond graph tool. This technique combines graphical and relational aspects to establish connections between bond graph elements, particularly in deducing junction relationships and employing bicausal inversion for trajectory tracking controller design. To determine the controller parameters, we utilized a meta-heuristic method called Firefly for optimization, thus avoiding the need for trial and error. The simulation was conducted using 20-Sim software and a Matlab/Simulink script, which yielded improved results. This paper presents an initial contribution that demonstrates the integration of meta-heuristic optimization and the bond graph tool for parameter selection in 20-sim simulation software.
Keywords: Bond graph. Maglev system. Asymptotic tracking control. Firefly optimization.

Resumo
Este artigo aborda a modelagem e controle de uma suspensão eletromagnética utilizando a ferramenta de gráficos de ligação (bond graph). Essa técnica combina aspectos gráficos e relacionais entre os elementos do gráfico de ligação, especialmente na dedução das relações de junção e na inversão bicausal para o projeto de um controlador de rastreamento de trajetória. Este último requer a escolha de parâmetros, o que nos levou a utilizar um método meta-heurístico, o Firefly, para sua otimização e evitar a tentativa e erro. A simulação demonstrou e apresentou melhores resultados utilizando o software 20-Sim e um script Matlab/Simulink. Este artigo oferece uma primeira contribuição entre a otimização meta-heurística e a ferramenta de gráficos de ligação para a escolha de valores de parâmetros sob o software de simulação 20-sim.
Palavras-chave: Gráfico de ligação. Sistema Maglev. Controle assintótico de rastreamento. Otimização Firefly.

1. Introduction

The main objective of the electromagnetic levitation systems is the handling of an object without direct contact with the object. This is done by using the magnetic force created by like it was electromagnetic, for different reasons. This objective allows the system MAGLEV to be among the subjects most inverted in the domains of scientific research, with the aim of modelling, simulation, control and diagnosis or others, which has also allowed us to introduce and apply this method of levitation in different industrial and domestic areas as transport by rail, levitation of goods in harbours/airports, sound systems (Baffles or High Talkers), etc.

There exist two main categories in systems MAGLEV (Vischer & Bleuler, 1993):

- Passive: used by superconductors.
- Active: used by a sensor for controlling the space between the system and the ground or suspended object.

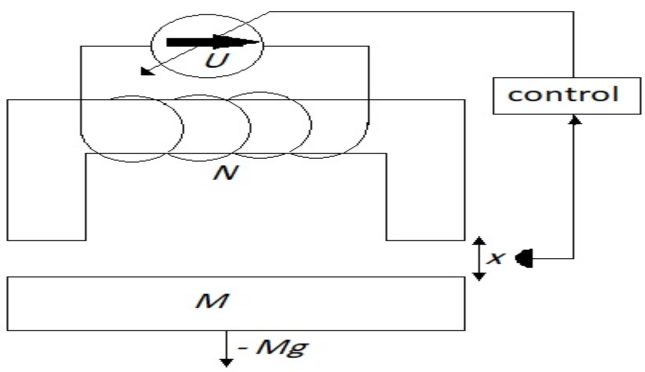
In this work, we treat the 2nd category, whose objective is the modelling by the bond graph, the famous multi-domain modelling tool invented by Prof H. Paynter (Paynter, 1961) and then developed by various researchers, to be an identification tool, analysis, diagnosis (Karnopp *et al.*, 1975) (Karnopp *et al.*, 1990) (Borutzky, 2010) (Merzouki *et al.*, 2013) (Sergio, 1993) (Sergio, 2001), then the design of the control law, based on the graphic technique developed by Sergio Junco (Sergio *et al.*, 2002), for a control law based on the 2nd method of Lyapunov. This law is applied in simulation on 20-sim, presents the difficulty of choice of the controller parameter, and has allowed us to give a solution by the employment of a meta-heuristic optimizer, based on the firefly algorithm which has known a wide application (Dif *et al.*, 2020) (Panda *et al.*, 2018) in different sectors.

This work shows the interaction of several concepts, Bond graph methodology, control law design and meta-heuristic optimization, which has given us better results allowing their practical implementation and/or applying this idea in other complex multi-domain systems.

2. State-of-the-art control of MAGLEV systems and BG model

The active MAGLEV system, also called AMB (Active Magnetic Bearing), consists of an electromagnetic circuit that will maintain a suspended ferromagnetic mass at a well-controlled distance (Figure 1):

Figure 1 - Synoptic diagram of an electromagnetic levitation system (MAGLEV).



This system is the subject of several research studies, with a view to their modelling and control by different techniques, such as conventional techniques such as control by PD/PID regulator (Vischer & Bleuler, 1993) (Bleuler *et al.*, 1994) (Arif *et al.*, 2019) (Duka *et al.*, 2016) (Salman *et al.*, 2016), Artificial intelligence techniques (fuzzy logic, neural networks) (Moinuddin *et al.*, 2000) (Mokhtari *et al.*, 1998) (Qin *et al.*, 2014) (Sun *et al.*, 2019), linearization techniques (El Hajjaji *et al.*, 2001) (Maggiore *et al.*, 2004) (Šuster *et al.*, 2012) (Balko *et al.*, 2017) (Khan *et al.*, 2019) for linear control of the system, control techniques based on stability studies and performance criteria, as the Backstepping control (Wai *et al.*, 2008), LQR control (Maggiore *et al.*, 2004) (Acero *et al.*, 2016) (Yaseen *et al.*, 2018), observers (Acero *et al.*, 2016) (Sharma *et al.*, 2017), predictive control (Qin *et al.*, 2014) (Zhang *et al.*, 2020), numerical resolution techniques (AR, ARX) (Qin *et al.*, 2014) (Gómez-Salas *et al.*, 2015).

The control techniques mentioned above are based on non-linear or linear mathematical models, allowing their developers to simulate and/or implement them in practice, giving acceptable results. However, there is some literature work on graphic modelling by the bond graph tool, which treats the MAGLEV system as a magnetic device or circuit (Longoria, 2002) (Karnopp *et al.*, 2012), used as a sensor or transducer (Grivon, 2017), part of a record memory circuit element (Calchand, 2014), electromagnetic suspension used in vehicles or others (Hayoun *et al.*, 2004) (Mishra *et al.*, 2013) (Mishra *et al.*, 2014) (Clemen *et al.*, 2016), actuating element in mechatronics (Merzouki *et al.*, 2013) (Das *et al.*, 2005) (Niţu *et al.*, 2017) and robotics (Niţu *et al.*, 2008).

The MAGLEV system finds the interconnection of three domains of physics: electricity, magnetism and mechanics. These domains find unique modelling in their different phenomena by the bond graph tool, while representing the transfer of inter-domain power by the variables of stress "*e*" and flux "*f*", under the following power relation:

$$P = e.f \tag{1}$$

More details on the bond graph modelling basics can be found in (Borutzky, 2010) (Merzouki *et al.*, 2013). In our case, the BG model adopted for the MAGLEV system is shown in the following figure:

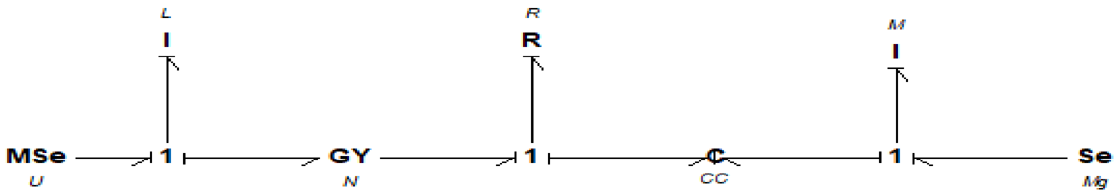


Figure 2 - MAGLEV Multi-Port Element Bond Graph Model.

The interconnection between the electric and magnetic domains is modelled by the mixed transformation element, the GY gyrator: N, with N being the number of winding turns, while between the magnetic and mechanical domains, there is a phenomenon of energy storage modelled by the multiport element "C" (Merzouki *et al.*, 2013) (Longoria, 2002) (Karnopp *et al.*, 2012) (Grivon, 2017) (Niţu, Niţu, & Grămescu, 2008). This multiport element has a matrix-type parameter, which is highly nonlinear, requiring linearization around their point of operation or equilibrium. For this, we have the following model:

$$\begin{cases} M = \frac{x}{\mu_0 A}\phi, magnetomotive\ force \\ F = \frac{\phi^2}{2\mu_0 A}, mechanical\ force \end{cases} \tag{2}$$

With: x: is the displacement;
A: is the air or the operating surface;
Φ: is the magnetic flux;
μ0: is the permeability of the air.

Around the equilibrium point, we can simplify the system of Equation (2) based on the principle of quadruple used in (Vischer & Bleuler, 1993) (Bleuler *et al.*, 1994), to represent the maglev system by the following system of equation (including the electrical part):

$$\begin{cases} F = k_i . i + k_s . x \\ U = L\frac{di}{dt} + k_i . v \end{cases} \tag{3}$$

With $\begin{cases} k_i = L\frac{i_0}{x_0}, \text{such as } i_0 \text{ and } x_0 \text{ are current and position at equilibrium point;} \\ k_s = k_i \frac{i_0}{x_0} \\ \text{v: is the speed of movement of the mass or the suspended object} \end{cases}$

This system of equation is modelled by a bond graph as follows (Merzouki *et al.*, 2013) (Mishra *et al.*, 2013):

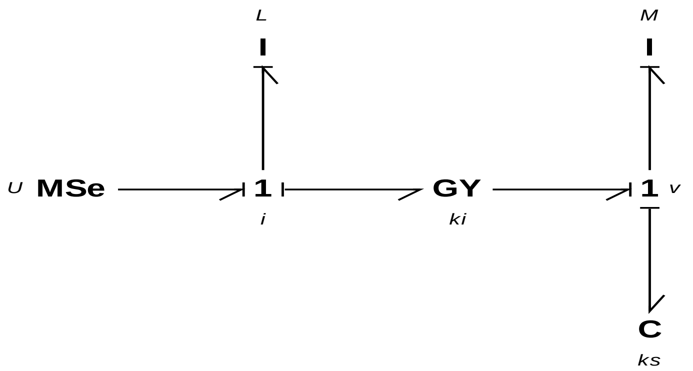


Figure 3 - Simplified MAGLEV Bond Graph Model.

This bond graph model is used for the design of the control law, based on graphical criteria, developed in the next section.

3. Control-based Bond graph model

The objective of any control law is certainly one of the following two objectives: regulation or trajectory tracking (Ogata, 2010).

The regulation consists in fixing the output of the system at a well-regulated value, against modelling errors and disturbance signals, as long as the problems of trajectory tracking consist in forcing the output of the system to follow a well-defined reference signal, often called an instruction.

Using the bond graph tool, based on the work of S. Junco (Sergio, 2001) (Sergio *et al.*, 2002), we can design a control law for trajectory tracking by using the characteristic laws from the junctions "1" and "0", using the Lyapunov principle for the stability of the sub-cascade shared systems along the I/O causal path (from the Se/Sf source to the De/Df detector), starting with the last subsystem to design an integration action, as in the backstepping controller. This technique has already been applied for the control of a DC motor (Sergio *et al.*, 2002) and also for the control of a spring-mass-damper system (Dif *et al.*, 2017), with efficiency even in the presence of uncertainty for tracking trajectory (Dif *et al.*, 2020). The Trajectory tracking law design procedure is as follows (Sergio *et al.*, 2002):

Table 1 - Procedure for designing a tracking trajectory law

Stages	Description
Step 1: Bicausal inversion	Inversion of the BG model along the causal path I/O by applying bicausality
Step 2: Deduction of the equation	Deduction of the inverse dynamic equation from the designated junction
Step 3: Substitution of the output	Definition of the output error from the subtraction operation between output and output
Step 4: Error Dynamics	Rewriting the system dynamic equation after defining the error dynamic
Step 5: Error substitution	Substitution of dynamic equation error for command law extraction

This procedure is recursively applied to all the sub-model bond graphs of the cascading system, until the main control law, which represents the controlled input of the system, is obtained.

4. Application of Tracking Control Law

The application of this procedure to our MAGLEV system, given by the bond graph model in the previous figure (Figure 3), led us to the following steps, after dividing into two subsystems as shown in the following figure:

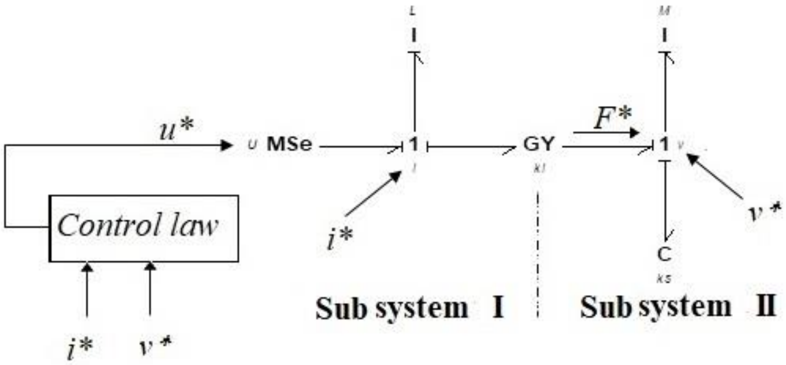


Figure 4 - Structure of the control law by bond graph

(a). Subsystem (II)

We apply the asymptotic tracking procedure to the subsystem (II), which gives us the following steps:

Step 1: Bicausal inversion: The bicausal inversion of a bond graph model consists of the application of bicausality, invented by P. Gawthrop (Gawthrop, 1995), for the synthesis of the command law, while dividing the causal line into two lines, as indicated in the following figure:

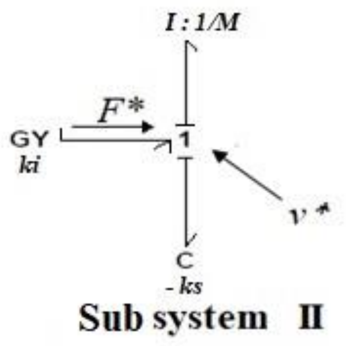


Figure 5: Bicausal Inversion of Subsystem II

Step 2: Inverse equation: According to the jonction law "1: v", we have:

$$F = M.\frac{dv}{dt} - \frac{1}{k_s}\int v\, dt \tag{4}$$

Step 3: Output substitution: We define the error between the desired trajectory and the actual output:

$$e_v(t) = v^*(t) - v(t) \text{therefore} v(t) = v^*(t) - e_v(t) \tag{5}$$

The relationship (4) then becomes:

$$F = M(\dot{v}^* - \dot{e_v}) - \frac{1}{k_s}\int (v^* - e_v)\, dt \tag{6}$$

Step 4: Error dynamics: We define the error dynamics by the following relation:

$$\dot{e_v}(t) + k_2.e_v(t) = 0, \text{ with } k_2 > 0 \tag{7}$$

Step 5: Error substitution: We replace the error and its derivative in the relation (6), and we obtain:

$$F^* = M\dot{v}^* + Mk_2v^* - \left(Mk_2v + \frac{1}{k_s}\int v\, dt\right) \tag{8}$$

It is the necessary force that allows the desired tracking *v*(t)* by the actual speed *v(t)*, without constraint.

(b). Subsystem (I)

The same procedure is followed for the subsystem (I)

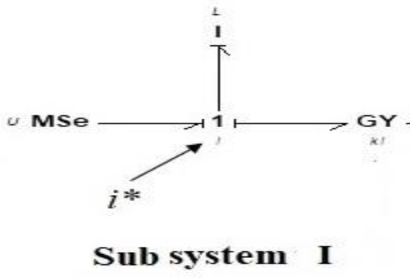


Figure 6 - Subsystem I bond graph model

Step 1: Bicausal inversion: The bicausal inversion of the bond graph model of subsystem I, lead to the following figure:

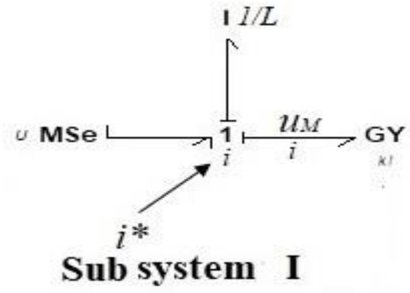


Figure 7 - Bicausal Inversion of Subsystem I

Step 2: Inverse equation:

According to the joining law "1: i", we have:

$$U = L.\frac{di}{dt} + u_M = L.\frac{di}{dt} + k_i.v \qquad (9)$$

Step 3: Output substitution:

The error between the desired current and the actual current is defined as:

$$e_i(t) = i^*(t) - i(t), \text{therefore}, i(t) = i^*(t) - e_i(t) \qquad (10)$$

The relationship (9) becomes:

$$U = L\frac{d}{dt}(i^* - e_i) + k_i.v \qquad (11)$$

Step 4: Error dynamics: The current error dynamics is defined by the following relation:

$$\dot{e_i}(t) + k_1.e_i(t) = 0, \text{ with } k_1\ 0 \qquad (12)$$

Step 5: Error substitution: We replace the derivative of the error in the relation (11), and we obtain:

$$U^* = L\frac{di^*}{dt} + Lk_1 i^* - Lk_1 i + k_i v \qquad \text{with } i^* = \frac{1}{k_i}F^* \qquad (13)$$

Deduced from the "$Gy{:}k_i$" gyrator, the final relation of the control law of tracking is as follows:

$$U^* = \frac{L}{k_i}\frac{dF^*}{dt} + \frac{L}{k_i}k_1.F^* - Lk_1 i + k_i v \tag{14}$$

With k_1 and k_2 being the parameters of the path tracker controller, which are chosen to minimize the error between the actual output and the predicted output.

With the help of the software 20-sim 4.8 viewer (Kleijn *et al.*, 2020), by their interface of an implementation of the bond graph models, we simulate the bond graph model of the electromagnetic suspension and the deduced trajectory tracking control law, with k_1*=300* and k_2*=600* controller parameter values, using system parameter values, as used in (Bleuler *et al.*, 1994).

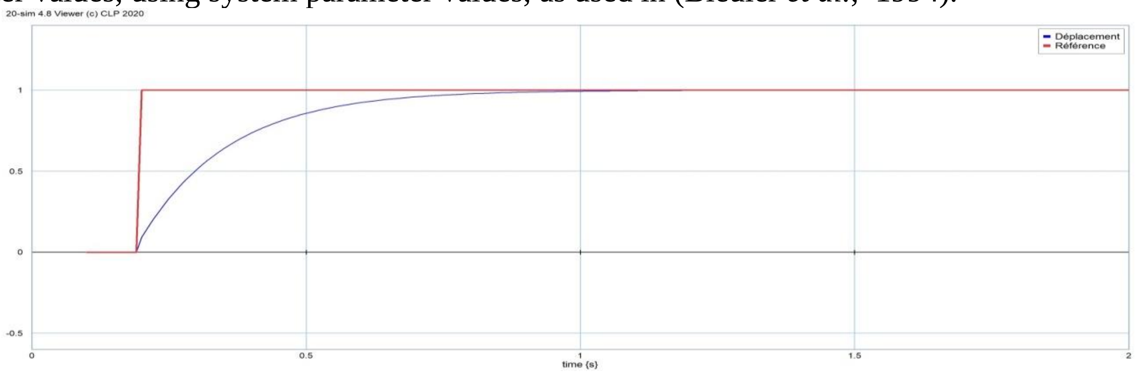


Figure 8 - Desired Movement Tracking Unit Step

In this figure, we see that the displacement signal follows the form of the reference signal (step unit), then we show in the following figure the error between the actual output and the reference:

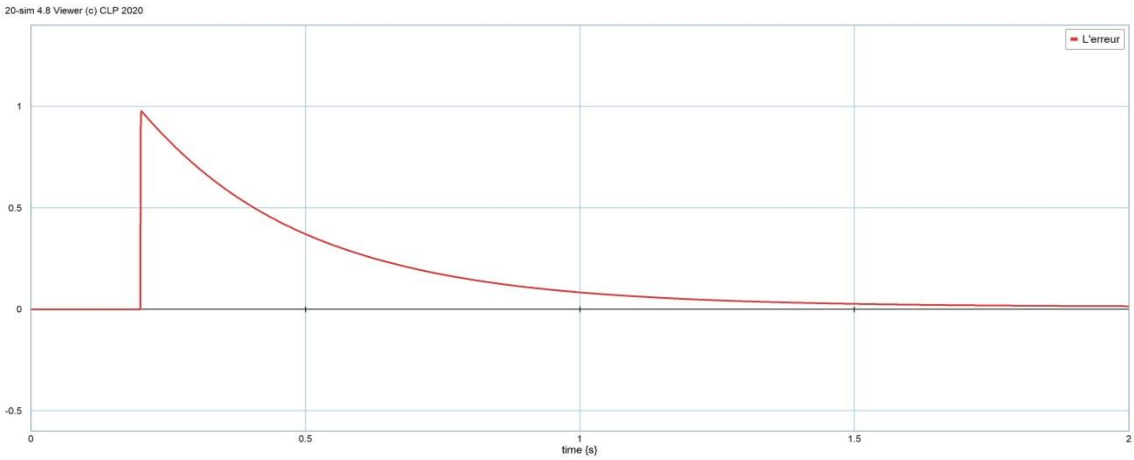


Figure 9 - Tracking error and calculated control law

This last figure shows that the error tends towards zero quickly, while the energy or the control needed for this follow-up is gradually reduced, but we note that the controller parameters are chosen arbitrarily, hence the need for an optimization method, which is used to calculate these parameters automatically, such as meta heuristic optimization methods, such as the Firefly method, described in the next section.

5. Firefly optimisation control for control parameters

Research in the international community does not stop using methods and algorithms inspired by nature to solve real problems of industry or others, such as the use of artificial intelligence: Fuzzy logic (Badoud *et al.*, 2022) for the design of a bond graph model-based controller, artificial neural networks (Qin *et al.*, 2014) for the control of magnetic levitation, and the use of meta-heuristic optimization algorithms, such as the grey wolf optimizer (Faris *et al.*, 2018) (Hatta *et al.*, 2019), the PSO (Laldingliana *et al.*, 2022) for the optimization of a fractional order PID controller of an electromagnetic suspension, which is also subject to the application of other meta-heuristic methods, Manta Ray Foraging optimization (Ekinci *et al.*, 2022), and in comparison between several optimization methods (Firefly, Grasshopper and ABC) for the concept of a PID regulator in (Gupta *et al.*, 2023).

The Firefly optimization method is a meta-heuristic method developed by Xin-She Yang (Yang, 2008), inspired by of fireflies' behaviour, who use light to communicate and attract their friends. This method has received a great deal of attention through its application in different systems, in particular in the identification of the parameters of an induction machine (Dif *et al.*, 2020), optimization of the parameters of the PID controller of a magnetic suspension (Gupta *et al.*, 2023), the rotational speed of a spinning machine (Vilas *et al.*, 2021) and others, so it has undergone developments and modifications in their operating principle (Kumar *et al.*, 2021).

The FA algorithm starts with an initial population of solutions, which are represented as fireflies in the algorithm. The fireflies represent potential solutions to the optimization problem, and their attractiveness is determined by their "brightness". Each firefly has a brightness value, which is a measure of the quality of the solution. The fireflies move in the search space, and their movements are determined by their brightness values. Brighter fireflies attract the less bright fireflies, and the less bright fireflies move towards the brighter fireflies. This simulates the process of fireflies attracting each other with their light. The movement of fireflies is guided by Equation (15). The equation describes the movement between two fireflies i and j:

$$x_i^{t+1} = x_i^t + \beta.\left(x_j^t - x_i^t\right) + \alpha * (rand - 0.5) \tag{15}$$

Where:
x_i^{t+1} is the location of firefly i at generation t+1,
x_i^t is the location of firefly i at generation t,
x_j^t is the location of firefly j at generation t,
β is the attractiveness coefficient,
α is the randomization coefficient.

The FA uses a randomization process which is represented in the third term in Equation (15) to explore different regions of the search space. This allows the fireflies to escape the local optima and converge to the global optima. The algorithm uses dynamic randomization of fireflies brightness values to improve the exploration of the search space. The FA is easy to implement and can be easily customized for different optimization problems.

The purpose of using the Firefly algorithm is to optimize and identify the controller parameters, avoid trial and error and minimize the error between the desired trajectory and the actual output of the system (displacement of the suspended mass) according to the following relationship:

$$\mathrm{e(t) = c(t) - x(t)} \tag{16}$$

To this end, we adopt the function of evaluation of the integral of the quadratic error, the most widespread in the evaluation of such problems (Dif *et al.*, 2020) (Gupta *et al.*, 2023):

$$f = \int_0^T e^2\,(t)dt \tag{17}$$

The general structure of our system is given by the following structure:

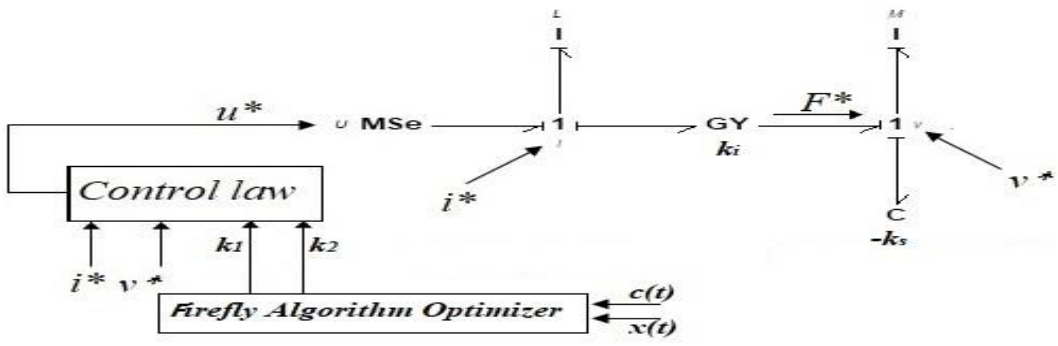


Figure 10 - Controller structure with Firefly optimizer

The simulation of our system is done using 20-sim software for the bond graph model and Matlab for the Firefly optimization of the controller parameters, as well as adopting the square signal as the reference signal. After optimizing the parameters, we found the following result:

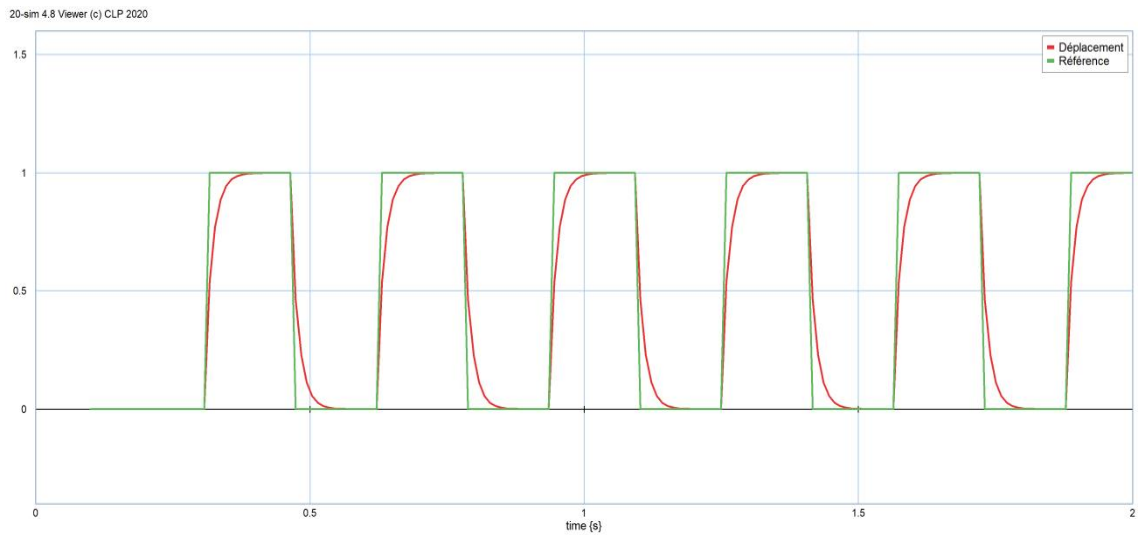


Figure 11 - The movement follows the trajectory

Our Firefly optimizer aims to identify two (02) parameters of the k1 and k2 controller, hence the number vector of the ‘x’ fireflies is (2), x=[x1; x2]. The population number of this vector is chosen (10), with the iteration number being '21' iterations, because our algorithm reaches its optimum faster.

In this respect, the controller parameters found by the Firefly algorithm have the following values: k1=2724.3, k2=277273.6. These parameters make it possible to give a meticulous track, with negligible error (Figure. 12):

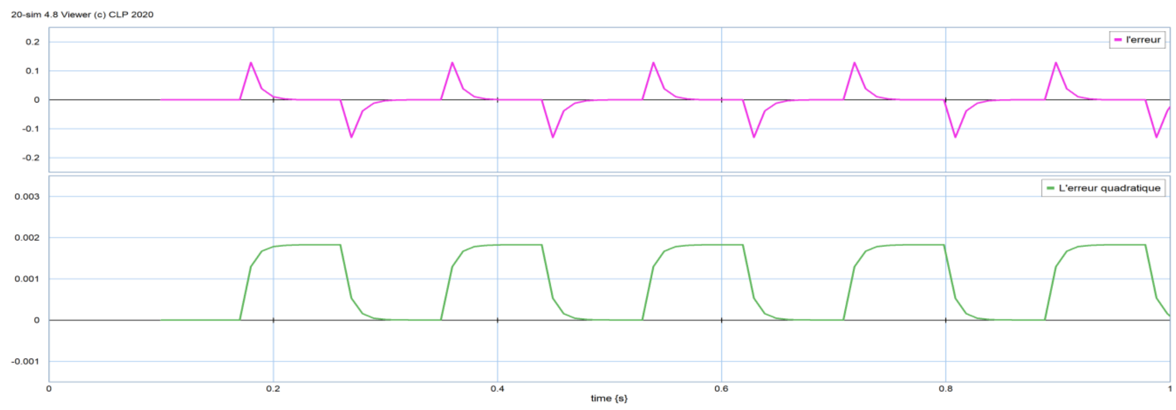


Figure 12 - The error and squared error

According to Figures 11 and 12, the output of the system (displacement) follows perfectly the reference of the square signal, with a much-reduced error (± 0.2) and minimal square error (< 0.002). This result is compared with other references (Duka *et al.*, 2016) (Salman *et al.*, 2016) (Qin *et al.*, 2014) (Šuster *et al.*, 2012) and looks better than him.

6. Conclusion

The main objective of this paper was the design of a law for controlling the trajectory of electromagnetic levitation based on a bond graph model and a graphic procedure. It is based on the inversion of the system, using the concept of bicausality in a bond graph. This method has proved to be effective in detecting the minimal error between the path and the output of the system; however, we have a problem choosing the controller parameters. Hence, the idea of using a meta-heuristic optimizer, that is the Firefly optimizer, gave us better solutions.

Additionally, the work proposes the use of the meta-heuristic optimization tool to identify parameters of the model bond graph or the deduced model (of state space or/ block diagram, transfer function).

References

Acero, A. R., Quiceno, J. A., & Bulies, J. A. (2016). Modelling and simulation of LQR and LFSV controllers in the Magnetic Levitation System (MLS). *Prospect*, *14*(1), 28-38.

Arif, M. A., Rasid, S. M., Hossain, M. B., Hoque, E. M., & Sarder, M. S. (2019). MODELING AND CONTROL OF A MAGNETIC LEVITATION SYSTEM USING AN ANALOG CONTROLLER. *Acta Electronica Malaysia, 3*(2), 41-44.

Badoud, A., Mekhilef, S., & Ould Bouamam, B. (2022). A Novel Hybrid MPPT Controller Based on Bond Graph and Fuzzy Logic in Proton Exchange Membrane Fuel Cell System: Experimental Validation. *Arabian Journal for Science and Engineering, 47*(3), 3201–3220.

Balko, P., & Rosinová, D. (2017). Modeling of magnetic levitation system. *21st International Conference on Process Control* . Strbske Pleso, Slovakia.

Bleuler, H., Vischer, D., Schweitzer, G., & Traxler, A. (1994). New concepts for cost-effective magnetic bearing control. *Automatica, 30*(5), 871-876.

Borutzky, W. (2010). *Bond Graph Methodology – Development and Analysis of Multidisciplinary.* London, UK: Springer.

Calchand, N. (2014). Modeling and control of magentic shape memory alloys using port-hamiltonian framework. Besançon, France: Thèse de l'Université de Franche-comté.

Clemen, L., Anubi, O. M., & Margolis, D. (2016). On the Regenerative Capabilities of Electrodynamic Dampers Using Bond Graphs and Model Predictive Control . *Journal of Dynamic Systems, Measurement, and Control , 138*(5), 051006 (7 pages).

Das, S., Krishnan, M., Yost, S. A., & Zimmerman-Oster, K. (2005). Advanced Mechatronics: Development of a Course on Modeling and Simulation of Mechatronic Systems. *The 2005 American Society for Engineering Education Annual Conference & Exposition.* Portland, Oregon.

Dif, I., Benmahammed, K., Kouzou, A., & Hafaifa, A. (2017). Bond Graph Synthesis Backstepping Control of Mass-Damping System. *The second International Conference on Applied Automation and Industrial Diagnostics.* Djelfa, Algeria.

Dif, I., Kouzou, A., Benmahammed, K., & Hafaifa, A. (2020). Trajectory tracking control design of a mass-damping-spring system with uncertainty using the bond graph approach. *Engineering, Technology & Applied Science Research, 10*(6), 6427-6431.

Dif, N., BOUDISSA, E., BOUNEKHLA, M., & Dif, I. (2020). Firefly algorithm improvement with application to induction machine parameters identification. *Revue roumaine des sciences techniques, Série Électrotechnique et Énergétique, 65*(1-2), 35-40.

Duka, A.-V., Dulău, M., & Oltean, S.-E. (2016). IMC Based PID Control of a Magnetic Levitation System. *Procedia Technology, 22*, 592-599.

Ekinci, S., Izci, D., & Kayri, M. (2022). An Effective Controller Design Approach for Magnetic Levitation System Using Novel Improved Manta Ray Foraging Optimization. *Arabian Journal for Science and Engineering, 47*(8), 9673–9694.

El Hajjaji, A., & Ouladsine, M. (2001). Modeling and nonlinear control of magnetic levitation systems. *IEEE Transactions on industrial Electronics, 48*(4), 831-838.

Faris, H., Aljarah, I., Al-Betar, M. A., & Mirjalili, S. (2018). Grey wolf optimizer: a review of recent variants and applications. *Neural Computing and Applications, 30*(2), 413–435.

Gawthrop, P. (1995). Bicausal Bond Graphs. *International Conference on Bond Graph Modeling and Simulation.* Las Vegas, USA.

Gómez-Salas, F., Wang, Y., & Zhu, Q. (2015). Design of a Discrete Tracking Controller for a Magnetic Levitation System: A Nonlinear Rational Model Approach. *Mathematical Problems in Engineering*, 360783.

Grivon, D. (2017). Design, Modelling and Sensing Possibilities of Magneto-Rheological Based Devices. Lausanne, Suisse: Thèse de l'École polytechnique fédérale de Lausanne.

Gupta , S., Debnath, S., & Biswas, P. K. (2023). Control of an active magnetic bearing system using swarm intelligence-based optimization techniques. *Electrical Engineering*.

Hatta, N. M., Zain , A. M., Sallehuddin, R., Shayfull, Z., & Yusoff , Y. (2019). Recent studies on optimisation method of Grey Wolf Optimiser (GWO): a review (2014–2017). *Artificial Intelligence Review*, *52*(4), pages 2651–2683.

Hayoun, R., Dif, I., Amara, S., Khemliche, M., & Mostefai, M. (2004). Modélisation par Bond graph d'une suspension électromagnétique (MAGLEV). *3ème Conférence sur le Génie Electrique (CGE"03).* Bordj El Bahri, Algérie.

Karnopp, D. C., Margolis, L., & Rosenberg, R. C. (1990). *System dynamics: A Unified Approach.* Wiley Publications.

Karnopp, D., & Rosenberg, R. C. (1975). *System Dynamics: A Unified Approach.* Michigan, USA: A. Wiley - interscience publications.

Karnopp, D., Margolis, D., & Rosenberg, R. (2012). *System Dynamics: Modeling, Simulation, and Control of Mechatronic Systems, 5th Edition.* New Jersey, USA: John Wiley & Sons Inc.

Khan, M. J., Khan, D., Siddiqi, S. J., Saleem, S., & Khan, I. (2019). Design & Control of Magnetic Levitation System ED-4810: Review and Stability Test. *Universal Journal of Electrical and Electronic Engineering, 6*(4), 191-202.

Kleijn , C., & Groothuis, M. A. (2020). *Getting Started with 20-sim 4.8.* Enschede, the Netherlands: Controllab Products B.V.

Kumar, V., & Kumar, D. (2021). A Systematic Review on Firefly Algorithm: Past, Present, and Future. *Archives of Computational Methods in Engineering, 28*(4), 3269–3291.

Laldingliana, J., & Biswas, P. K. (2022). Artificial Intelligence Based Fractional Order PID Control Strategy for Active Magnetic Bearing. *Journal of Electrical Engineering & Technology, 17*(6), 3389–3398.

Longoria, R. (2002). Magnetic circuits and device modeling. Austin: Department of Mechanical Engineering The University of Texas at Austin.

Maggiore, M., & Becerril, R. (2004). Modelling and control design for a magnetic levitation system. *International Journal of Control, 77*(10), 964-977.

Merzouki, R., Samantaray, A. K., Pathak, P. M., & Ould Bouamama, B. (2013). *Intelligent Mechatronic Systems: Modeling, Control and Diagnosis.* London, UK: Springer-Verlag.

Mishra, A. K., Kumar, R., & Sarangi, S. (2014). Mathematical Modeling of Electromagnetic Levitation Based Active Suspension using Bond Graph. *Journal of Applied Mechanics and Materials , 575*, 785-789.

Mishra, A., Raina, R., Yadav, S., Verma, A., Sarangi, S., & Saha, A. (2013). Modeling and Simulation of Levitating Ball by Electromagnet using Bond Graph. *1st International and 16th National Conference on Machines and Mechanisms* . IIT Roorkee, India.

Moinuddin, Siddiqui, A., Sharma, A., & Gupta, J. (2000). A Multi-Level Fuzzy Rule Based Control Strategy for Maglev System. *EPE Journal, 10*(1), 26-31.

Mokhtari, M., & Marie, M. (1998). *Applications de MATLAB 5 Et Simulink 2.* Paris, France: Springer-Verlag.

Niţu, C., Grămescu, B., & Avram, M. (2017). Bond graphs modelling of electromagnetic actuators. *International Journal of Mechatronics and Applied Mechanics*, *1*(1), 118-123.

Niţu, C., Niţu, S., & Grămescu, B. (2008). Electromagnetic actuator modeling for modular robotics applications. *Journal of Optoelectronics and Advanced Materials*, *10*(5), 1137-1142.

Ogata, K. (2010). *Modern Control Engineering 5th Edition.* Upper Saddle River, New Jersey, USA: Prentice Hall.

Panda, M., Dutta , S., & Pradhan , S. (2018). Hybridizing Invasive Weed Optimization with Firefly Algorithm for Multi-Robot Motion Planning. *Arabian Journal for Science and Engineering, 43*(1), 4029-4039.

Paynter, H. M. (1961). *Analysis and design of engineering systems.* Boston, USA: The MIT Press.

Qin, Y., Peng, H., Ruan, W., Wu, J., & Gao, J. (2014). A modeling and control approach to magnetic levitation system based on state-dependent ARX model. *Journal of Process Control, 24*(1), 93-112.

Salman, A., Van-Duc, D., & Takafumi, K. (2016). Electromagnetic levitation control with sensorless large air gap detection for translational motion application using measured current-ripple slope. *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society.* Florence, Italy.

Sergio, J. (1993). Stability Analysis and stabilizing control Synthesis via Lyapunov's second Method Directly on bond graphs of nonlinear systems. *19th Annual Conference of IEEE Industrial Electronics*, (pp. 2065-2069). Maui, HI, USA.

Sergio, J. (2001). A Bond graph Approach to control systems synthesis. *Proc. of ICBGM'2001*, (pp. 125-130). Phoenix, USA.

Sergio, J., Garnero, G., & Donaire, A. (2002). Suivi de trajectoire de vitesse du moteur série à CC : une approche Bond Graph. *Conf. Int. Francophone d'Automatique.* Nantes, France.

Sharma, D., Shukla, S. B., & Ghosal, S. K. (2017). Modelling and state estimation for control of magnetic levitation system via a state feedback based full order observer approach. *IOP Conference Series: Materials Science and Engineering.* Sikkim, India.

Sun, Y.-G., Xu, J.-Q., Chen, C., & Lin, G.-B. (2019). Fuzzy H∞ robust control for magnetic levitation system of maglev vehicles based on T-S fuzzy model: Design and experiments. *Journal of Intelligent & Fuzzy Systems, 36*(2), 911-922.

Šuster, P., & Jadlovská, A. (2012). Modeling and control design of Magnetic levitation system. *IEEE 10th International Symposium on Applied Machine Intelligence and Informatics (SAMI),* (pp. 295-299). Herlany, Slovak Republic.

Vilas, K. J., & Asutkar, V. G. (2021). A novel optimal firefly algorithm based gain scheduling proportional integral derivative controller for rotor spinning machine speed control. *International Journal of Dynamics and Control, 9*(4), 1730–1745.

Vischer, D., & Bleuler, H. (1993). Self-sensing active magnetic levitation. *IEEE Transactions on Magnetics, 29*(2), 1276-1281.

Wai, R. -J., & Lee , J. -D. (2008). Backstepping-based levitation control design for linear magnetic levitation rail system. *IET Control Theory & Applications, 2*(1), 72-86.

Yang, X. S. (2008). *Nature-Inspired Metaheuristic Algorithms.* Frome, United Kingdom: Luniver Press.

Yaseen, M. H., & Abd, H. J. (2018). Modeling and control for a magnetic levitation system based on SIMLAB platform in real time. *Results in Physics, 8*, 153-159.

Zhang , Z., Zhou , Y., & Tao , X. (2020). Model predictive control of a magnetic levitation system using two-level state feedback. *Measurement and Control, 53*(5-6), 962-970.