Tekhnê

Tecnología al servicio de la sociedad

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- Superior derecha: Superior derecha: Complete system block diagram (Cruz, K. and Vera, F.)
- Centro: Design area (Cruz, K. and Vera, F.)
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- Inferior derecha: Low-pressure effect on the line flock (Martínez, F.)

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Volume 18 - Number 1 - 2021

Index

Articles

Editorial

Nuestra actual sociedad es muy diferente a la experimentada por generaciones anteriores, incluso hace tan solo 10 años la tecnología y las tendencias de desarrollo eran bastante diferentes. Hoy en día es fácil para la mayor parte de la población contar en sus bolsillos con un dispositivo electrónico de alta capacidad computacional, cámara digital, continuamente conectado, y con una gran variedad de sensores. Los teléfonos inteligentes han encontrado un nicho propio dentro de nuestra cultura, más allá de lo logrado por los computadores personales y las extintas agendas electrónicas. Ellos existen debido al mercado, pero también a la disponibilidad tecnológica y la alta reducción en costos que permitió su masificación.

No son los únicos dispositivos digitales con estas características, pero si los más comercializados. Y gracias a la existencia de todos ellos, en conjunto con Internet, redes de sensores, drones y robots de servicios, entre otros, se ha incrementado la cantidad de datos disponibles para análisis de comportamientos y tendencias, lo que en conjunto con las nubes de almacenamiento y servidores especializados en procesamiento de datos, ha impulsado más que nunca el uso del aprendizaje automático, y su hijo más conocido, el aprendizaje profundo, en el desarrollo de servicios personalizados tanto a nivel industrial, médico, comercial e incluso educativo.

Los profesionales de esta nueva generación tienen un gran reto, particularmente importante en los países en vía de desarrollo, y es el de capitalizar estas tecnologías para impulsar el desarrollo económico del país. Si bien la brecha económica entre países desarrollados y no desarrollados es mayor que nunca, la experiencia de muchos países demuestra que es la tecnología la clave para reducir estas desigualdades, de la mano con un apoyo y política estatal inteligente y estratégica.

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Editorial

Our current society is very different from that experienced by previous generations, even as recently as 10 years ago technology and development trends were quite different. Today it is easy for the majority of the population to carry in their pockets an electronic device with high computing power, a digital camera, continuously connected, and with a variety of sensors. Smartphones have found their niche in our culture, beyond that of personal computers and the extinct PDAs. They exist because of the market, but also because of the technological availability and the high reduction in costs that allowed their massification.

They are not the only digital devices with these characteristics, but they are the most commercialized. And thanks to the existence of all of them, together with the Internet, sensor networks, drones, and service robots, among others, the amount of data available for behavioral and trend analysis has increased, which, together with storage clouds and specialized data processing servers, has boosted more than ever the use of machine learning, and its best-known child, deep learning, in the development of personalized services at industrial, medical, commercial and even educational levels.

Professionals of this new generation have a major challenge, particularly important in developing countries, and that is to capitalize on these technologies to drive the country's economic development. While the economic gap between developed and undeveloped countries is wider than ever, the experience of many countries shows that technology is the key to reducing these inequalities, hand in hand with intelligent and strategic government support and policy.

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Review of flocking organization strategies for robot swarms

Revisión de las estrategias de organización en bandadas para enjambres de robots

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Robotics promises great benefits for human beings, both at the industrial level and concerning personal services. This has led to the continuous development and research in different problems, including control, manipulation, human-machine interaction, and of course, autonomous navigation. Robot swarm systems promise an alternative solution to the classic high-performance platforms, particularly in applications that require task distribution. Among these systems, flocking navigation schemes are currently attracting high attention. To establish a frame of reference, a general review of the literature to date related to flocking behavior, in particular, optimized schemes with some guarantee of safety, is presented. In most of the cases presented, the characteristics of these systems, such as minimal computational and communication requirements, and event-driven planning, are maintained.

Keywords: Emergence, flocking, multi-agent systems, path planning, swarm systems

La robótica promete grandes beneficios para el ser humano, tanto a nivel industrial como con respecto a servicios personales. Esto ha incidido en el continuo desarrollo e investigación en diferentes problemas, entre ellos el control, la manipulación, la interacción hombre-máquina, y por supuesto, la navegación autónoma. Los sistemas de enjambres de robots prometen una alternativa de solución frente a las clásicas plataformas de alto de desempeño, particularmente en aplicaciones que requieren distribución de tareas. Entre estos sistemas, llama la atención los esquemas de navegación en bandada, los cuales tiene actualmente una alta atención. Para establecer un marco de referencia, se presenta una revisión general de la literatura a la fecha relacionada con comportamientos en bandada, en particular esquemas optimizados y con alguna garantía de seguridad. En la mayoría de los casos presentados se mantienen las características de estos sistemas, como son requisitos mínimos de computación y comunicación, y la planificación basada en eventos.

Palabras clave: Bandada, emergencia, planificación de trayectorias, sistemas de enjambre, sistemas multiagentes

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Introduction

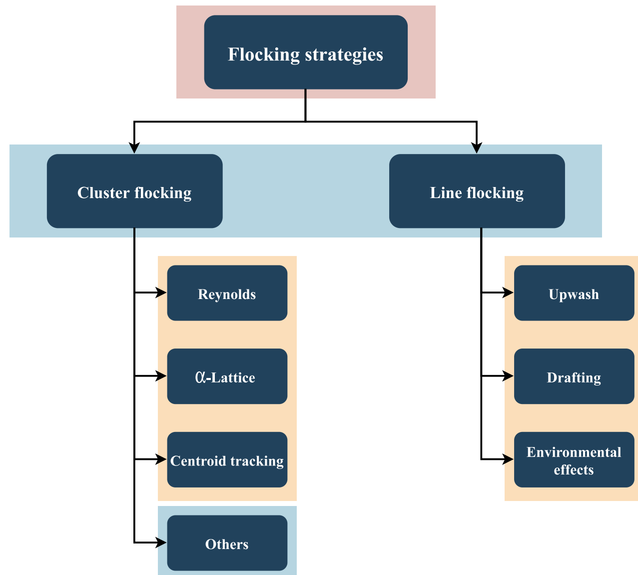
It can be stated that the study of swarm behavior in multi-agent systems started from the three heuristic rules proposed by Reynolds in 1987 (Reynolds, 1987). This model is known as Reynolds' classical behavior and is based on two measures of the multi-agent swarm, the area of the group and the polarization. From these measures, the model proposes the design of applications, and it is possible to observe the variation in the behavior of the system by varying the individual values of these parameters. From these ideas, initially simulated by computer, several applications of robotic flocking involving coordinated delivery, reconnaissance, surveillance, and mobile sensor networks have been proposed (Martínez & Delgado, 2012; Semnani & Basir, 2017; Xiao et al., 2018; W. Yuan et al., 2020). These ideas have been able to take advantage of the most recent advances in processing power and low energy consumption to implement robotic swarm applications with high adaptability, scalability, and robustness (Martínez et al., 2018; Oh et al., 2017). Even so, research in this field remains an open engineering problem due to the constraints imposed by a large swarm, both in control and cost. A robot, or agent, in a multi-agent system, must be endowed with limited sensing, communication, actuation, memory, and computational capabilities. Size concerning the environment and the task is also very important, and everything must fit together with optimized power consumption schemes.

Flocking behavior emerges as a consequence of specific rules executed individually by each agent. In this sense, many researchers have proposed decentralized control alternatives that lead to flocking behavior (Barve & Nene, 2013; Bayındır, 2016; Zhu et al., 2016). Much of the early work in this direction was proposed to demonstrate the functionality of the system, without considering optimal operating conditions. It was normal at the time to consider the self-organization problem and the optimal performance problem as two independent problems (Fine & Shell, 2013). More recent design approaches consider the two problems as simultaneous design objectives, thus requiring a single design scheme (Beaver et al., 2020; Wilson et al., 2020).

If we think of a way to classify the different flock control schemes, it is correct to refer to the very characteristics of this behavior in biological systems, the initial source of inspiration. From this point of view, it is possible to separate the behavioral models into two categories. The first category is characterized by group flocking, or cluster flocking, as observed, for example, in the movement of sparrows. The second category has different grouping rules and resembles more the movement on a line, known as line flocking, for example in the movement of geese (Fig. 1). This same classification is used in this paper to characterize the different schemes found in the literature. As in different groups of birds, different flocking behaviors have different

Figure 1

Flocking strategies according to clustering form (Beaver & Malikopoulos, 2021).



applications, and of course, different behavioral rules and implementation. Even so, engineering schemes can be much richer in options and implementations than those found in nature.

Our research focuses more on cluster approaches, yet this review presents the two flocking models as an important starting background. There are also limitations of technical content in the compilation due to the restricted space available. In any case, the details and fundamental concepts of each case are presented, and the future development of this field of research is projected.

Problem statement

A robot swarm is a multi-agent system whose behavior emerges as a consequence of simple rules executed by each agent in response to events or stimuli detected in the environment. This system is composed of $N \in \mathbb{N}$ agents from a finite population indexed by the set $\mathcal{A} = \{1, 2, 3, \cdots, N\}$. Each of these agents is assigned position and velocity properties in the navigation environment $\mathcal{W} \subset \mathbb{R}^2$. The position of the agent i is defined by the vector $\boldsymbol{p}_i(t)$, and its velocity by the vector $\boldsymbol{v}_i(t)$, both parameters defined in the interval $t \in \mathbb{R}_{\geq 0}$. The environment $\mathcal{W}$ is compact and planar, with a limiting boundary $\partial\mathcal{W}$ that restricts the motion of the agents. The agents are small concerning $\mathcal{W}$, so they are modeled as points with specific kinematics. The state of

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each agent is defined by the state vector $\boldsymbol{x}_i(t)$, so the state of the system is set by Eq. 1.

$$\boldsymbol{x}(t) = \left[\boldsymbol{x}_1^T(t), \boldsymbol{x}_2^T(t), \cdots, \boldsymbol{x}_N^T(t)\right]^T \quad (1)$$

The state of each agent is not explicitly controlled, which is why it is not important to measure its state precisely. Instead, the coordination of the system is relegated to the fact that the agents satisfy a trajectory that follows some high-level property. For any region, $R \in \mathcal{W}$ it is assumed that each agent moves on a trajectory according to the behavior of the neighborhood of robots $N_i(t) \subseteq \mathcal{A}$ to which it belongs. This neighborhood is formed by all agents near agent i that agent i can sense and/or establish communication with, including agent i. Consequently, the neighborhood can be defined in different ways according to the coordination strategy of the system, which includes distance between agents, information radiated by the agents, k-nearest neighbors, geometric partitions of the environment, or specific landmarks in the environment. The neighborhood of an agent is in general a fraction of the system but can encompass all agents depending on the specific topology.

The obstacle set $\mathcal{O}$ consists of a finite number of inaccessible regions in $\mathcal{W}$. These regions are enumerable, closed, and share the same properties as $\partial\mathcal{W}$ in that they limit the movement of agents. The free space through which the agents can navigate is defined as $E = \mathcal{W} - \mathcal{O}$. The control of the agent i is developed during the evolution of the system according to a policy. State feedback is not performed in general, instead, information feedback is performed using filters. A filter is a mapping of the form $\phi : \mathcal{I} \longrightarrow Y$ where $\mathcal{I}$ corresponds to the information space that is designed for the task (Bobadilla et al., 2012), and is defined with each observation Y of the agent.

Clusters and swarms

In biology, the movement of small birds in groups is known as cluster flocking (Sankey & Portugal, 2019). Among the advantages of this type of joint movement, it is postulated that it facilitates predator avoidance by extending the sensing range and rapid group communication of the swarm. It is also believed to serve the system to estimate population size and coordinate collective actions. These hypotheses are under investigation, as well as whether or not this type of navigation requires a leader (hierarchical flocking). All these cases are considered equally in this review.

A group of continuously moving agents forms a flocking cluster if there is a finite distance between any pair of agents in the swarm for an instant and all agents in the swarm. The fact that the agents remain within a defined diameter is what defines the cohesion parameter of the swarm. In addition, the agents must converge continuously over time, but without explicit formation. Each agent in the system can detect some other neighboring agents at a certain instant of time, according to its sensing and communication capacity (partial observation). From this information, it must establish its relative location in the system and its movement strategy. Consequently, most cluster flocking strategies simulate the continuous update of the control policies of each agent, while evaluating the overall cost of the system (energy and task time) (Martínez et al., 2012).

Undoubtedly, the cluster flocking scheme with the largest number of implementations in the specialized literature is the one that seeks to replicate Reynolds' basic behavioral rules (Reynolds, 1987): collision avoidance, velocity matching, and flock centering. The simplest way to implement these rules is to apply a cost function J to each agent consisting of two parts, a first one in charge of collision avoidance, and a second one with the task of guaranteeing the velocity alignment of the agent. If the relative position between two agents of the system $i, j \in \mathcal{A}$ is defined as (Eq. 2):

$$\boldsymbol{s}_{ij}(t) = \boldsymbol{p}_i(t) - \boldsymbol{p}_j(t) \quad (2)$$

Then, the cost function for agent $i \in \mathcal{A}$ with respect to agent $j \in N_i(t)$ (the neighborhood of agent i at instant t), can be defined in general form as follows (Eq. 3):

$$J_i = V\left(\left\|\boldsymbol{s}_{ij}(t)\right\|\right) + \sum_{j \in N_i(t)} \left\|\dot{\boldsymbol{s}_{ij}}(t)\right\|^2 \quad (3)$$

Since V is in charge of avoiding collisions, this function is configured as a potential field that defines local attraction-repulsion forces for agent i with respect to its neighborhood $N_i(t)$. Eq. 3 allows defining the motion strategy of agent i from the instantaneous location of the neighboring agents (Fig. 2).

One such group behavior scheme is α-lattice (Olfati-Saber, 2006). In this algorithm it is proposed to use a distance d that minimizes the potential field defined by V, and which is set as the distance that any agent $i \in \mathcal{A}$ must satisfy concerning its neighbors $j \in N_i(t)$, that is (Eq. 4):

$$\left\|\boldsymbol{s}_{ij}(t)\right\| = d \quad (4)$$

Since this definition coincides with the global minimum of the cost function J, it is widely used in many schemes to define the flocking rules in multi-agent systems, differentiating each strategy in the motion planning algorithms. In this sense, two approaches can be differentiated, those with reactive behavior without prior knowledge of the environment, and planning approaches that use some a priori information from the environment. In the first group, agents consider local information, including the behavior of their neighbors, to establish a movement strategy while respecting the basic rules of flocking (Morihiro et al., 2006a, 2006b). This local information usually comes from the state detected in the neighbors, which is continuously

Tekhnê
January - June 2021, Vol. 18, No. 1, pp. 13 – 20

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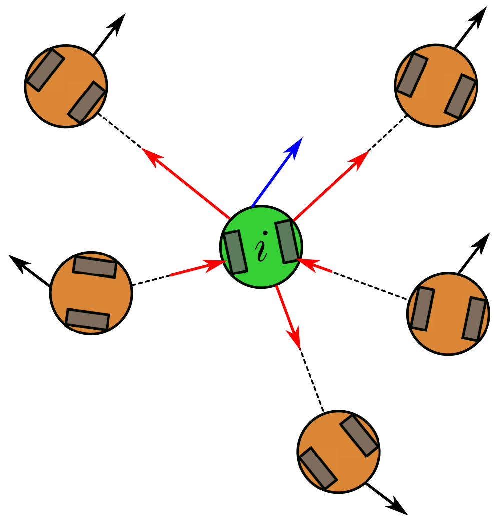
Figure 2

Definition of the movement strategy of agent i based on the behavior of its neighboring agents.



updated, but in other schemes predator information is included as additional populations to force movement or global references in the environment (C. Wang et al., 2018) to avoid sub-groups of agents in the system (Camperi et al., 2012; Fine & Shell, 2013).

In these reactive strategies, considerable work has been done on the problem of optimal Reynolds rule-following. In this sense, schemes have been proposed with constraints on the system states (Qiu & Duan, 2020), estimation of the possible optimal states of the agents from models based on neural networks (Navarro et al., 2015), constraints on the control inputs (Celikkanat, 2008), and constraints on the environment and the agents (Vásárhelyi et al., 2018). In the vast majority of these investigations, navigation is ensured by avoiding collisions based on the computation of potential field strengths. However, this strategy has widely known convergence problems, which brings this problem back to the research field in schemes in which the agent's motion is restricted to safe trajectories that minimize its energy consumption (constraint-driven approach) (Egerstedt et al., 2018; Ibuki et al., 2020).

As an alternative to reactive strategies, there are also planning approaches in which each agent plans an optimal trajectory based on the information it already possesses from the environment and its neighbors. In general terms, this type of strategy presents a better behavior of the agent in terms of performance (convergence and movement), but at a high computational cost, which poses much higher requirements for the design of each agent. It is also important to note that these schemes, by concept, do not have a central control system, so the update of the system information along the agents is very complex, opting for state estimation schemes (Dave & Malikopoulos, 2020; Nayyar et al., 2013). These problems are solved in some cases by establishing communication links between nearby agents (Morgan et al., 2016), limiting planning to only a few agents in the system among which information is shared (Dave & Malikopoulos, 2019), and applying predictive models in which agents recalculate their strategy each time they obtain new information from the system (Jafari et al., 2020; Xu & Carrillo, 2017; Q. Yuan et al., 2017; Zhang et al., 2008).

Within optimal control research, the center-of-mass tracking problem has become popular. This is a general approach to many engineering problems, but in the specific case of cluster flocking it seeks to define the center of mass of the swarm (virtual leader), which must follow the reference trajectory, and whose state is always known to all agents. This design concept is addressed by including a term in Eq. 3 that allows for the reference's state to be followed and thus can be solved using both reactive and planned schemes. As a result, the general Reynolds flocking rules hold, i.e., each agent only handles the information of its neighborhood, so the virtual leader tracking problem becomes an optimization problem because no agent handles the state information of the entire system globally (Hayes & Dormiani-Tabatabaei, 2002; La et al., 2015; La et al., 2009).

Line flocking

Line flocks are behaviors observed in certain birds, such as geese, in which agents travel in a V-shape, not in an unshaped cluster of agents. This behavior is observed in some large birds in migratory processes and has been determined to have large energy savings for individuals when traveling long distances (Gatt et al., 2020; Kölzsch et al., 2020). This energetic characteristic is what makes it interesting for multi-agent systems in the development of tasks that require large displacements, and the inability to recharge along the way. The advantage in birds lies in the possibility of suspending themselves in the ascending winds caused by the leading bird, reducing their energy consumption (Fig. 3). Similar advantages are found in other types of displacements such as terrestrial and underwater, such as the possibility of taking advantage of the low-pressure wake that the leading agent leaves behind it to reduce the force required by the other agents in the system (Beaumont et al., 2017; Ouvrard et al., 2018).

To reach line flocking in an artificial system, the shape of the swarm is more important than the distance to its neighbors. To achieve this simply, it is common to define formation points based on the characteristics of the system, i.e., the wake that each agent produces when moving in the environment for which it has been designed (Nathan & Barbosa, 2008). This is a new control problem, in which

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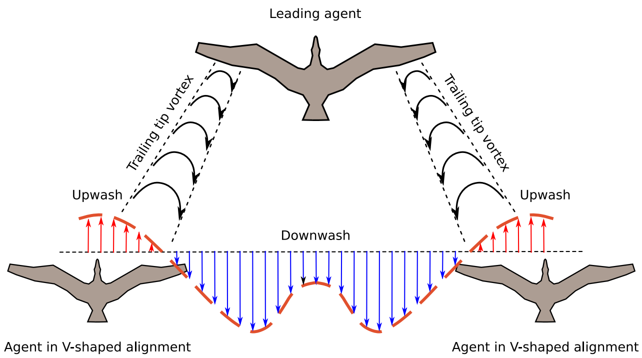
Figure 3

Low-pressure effect on the line flock. The flock leader induces upwash and downwash in its wake with its wings and tail, which are used by the other birds to sustain themselves and reduce energy costs.



the important thing is that each agent reaches its formation point in the time defined for it (in most cases, the shortest possible time) (Mirzaeinia et al., 2019). This type of control is complex to perform autonomously by each agent, which in general changes the control structure to a centralized one (W. Wang et al., 2020; Yang et al., 2018). Moreover, in the biological model, birds consider the particular characteristics of each agent to establish its position in the flock, such as age and size, elements that become meaningless in the artificial approach, since in principle all agents are identical, so in general their position in the flock is fixed. Schemes of reconfiguration of the agents in ways other than V-formation are outside the focus of this research and are therefore not documented. It is worth noting, however, that there is a variant of line flocking that also seeks energy savings in agent displacement while taking into account the aerodynamic and hydrodynamic interactions between the agents (Bedruz et al., 2019). This criterion can be used to define an agent's ideal distance from its neighbors, and thus a flock structure that meets the requirements of line flocking.

Interestingly, however, some works show that line flocking emerges as a consequence of simple rules executed by each agent, as occurs in cluster flocking (Yang et al., 2016). For this behavior to emerge, it is necessary to adjust the direction and velocity of each agent according to the upwash vectors, while minimizing the occlusion of the sensing field of each agent by the agents producing the low pressure. This approach somehow achieves a meeting point between the cluster and line schemes, showing that the difference between them lies in the objectives to be maximized in the self-organization policies of the system. Following this same principle, it is possible to adjust the agent's movement rules to respond to environmental conditions of wind and turbulence (Song et al., 2017). When the environment is particularly hostile and changing, moving against the current results in higher energy consumption, whereas taking advantage of these flows, even when it means changing the direction of travel slightly, can result in considerable energy and time savings in the end (Alam et al., 2018).

Other cluster flocking

This section is devoted to a set of approaches that have demonstrated flocking behavior without strictly following the basic Reynolds behavior rules. We have already discussed that line flocking can come to be considered a particular case of cluster flocking, but in the investigations described here similar behavior to cluster flocking is achieved (hence its location in Fig. 1) without using the same design approach. This is the case of a system that uses local measurements not directly related to neighboring agents to estimate the movement strategy of each agent to maximize the speed of the virtual leader (Vatankhah et al., 2009). Another case with a similar approach worth mentioning uses the anisotropy in the angle between neighbors as a flock structure estimation parameter (Makiguchi & Inoue, 2010).

Another approach proposes deriving each agent's movement from the ergodic trajectories defined by the other agents, which is equivalent to a mass vector of the system over time, and using this information to estimate which positions in the environment the system has visited (Veitch et al., 2019). This, however, does not guarantee flock behavior, which is why they supplement the scheme by limiting the agents' positions to the interior of a circle. There are also approaches in which the force driving the movement of the agents comes from somewhere other than the environment or other agents (Genter, 2017).

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Conclusion

The last two decades have shown a great deal of research activity related to multi-agent systems with flocking behavior. Much of this work is derived from the basic control rules postulated by Reynolds, with variations that seek to improve the behavior of the system throughout a task, optimize its displacement, energy consumption, and even its cost through the use of hardware of smaller computational capacity and size. Although centralized control schemes

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exist, the original idea derived from the biological model prevails, in which each agent autonomously defines its movement strategy based on its readings and control rules. Although it is possible to categorize the different proposals for flocking schemes, the fact is that they all respond to specific control rules based on the information that the agent gathers from its neighborhood, the environment, or external elements. This is true even for schemes that do not strictly follow Reynolds' behaviors. This remains an area of great research interest, but there are still unsolved problems regarding the information required for control, its processing, availability, and performance in terms of time and energy.

References

Alam, T., Reis, G. M., Bobadilla, L., & Smith, R. N. A data-driven deployment approach for persistent monitoring in aquatic environments. In: *2018 second IEEE international conference on robotic computing (IRC)*. 2018, 1–6. https://doi.org/10.1109/IRC.2018.00030.

Barve, A., & Nene, M. (2013). Survey of flocking algorithms in multi-agent systems. *IJCSI International Journal of Computer Science Issues*, *10*(6), 110–117.

Bayındır, L. (2016). A review of swarm robotics tasks. *Neurocomputing*, *172*, 292–321. https://doi.org/10.1016/j.neucom.2015.05.116

Beaumont, F., Taïar, R., & Polidori, G. (2017). Preliminary numerical investigation in open currents-water swimming: Pressure field in the swimmer wake. *Applied Mathematics and Computation*, *302*(1), 48–57. https://doi.org/10.1016/j.amc.2016.12.031

Beaver, L., Chalaki, B., Mahbub, A., Zhao, L., Zayas, R., & Malikopoulos, A. (2020). Demonstration of a time-efficient mobility system using a scaled smart city. *Vehicle System Dynamics*, *58*(5), 787–804. https://doi.org/10.1080/00423114.2020.1730412

Beaver, L., & Malikopoulos, A. (2021). An overview on optimal flocking. *Annual Reviews in Control*, *51*, 88–99. https://doi.org/10.1016/j.arcontrol.2021.03.004

Bedruz, R. A. R., Maningo, J. M. Z., Fernando, A. H., Bandala, A. A., Vicerra, R. R. P., & Dadios, E. P. Dynamic peloton formation configuration algorithm of swarm robots for aerodynamic effects optimization. In: *2019 7th international conference on robot intelligence technology and applications (RiTA)*. 2019, 264–267. https://doi.org/10.1109/RITAPP.2019.8932871.

Bobadilla, L., Martinez, F., Gobst, E., Gossman, K., & LaValle, S. Controlling wild mobile robots using virtual gates and discrete transitions. In: *2012 american control conference (ACC)*. IEEE, 2012, 1–8. https://doi.org/10.1109/ACC.2012.6315569.

Camperi, M., Cavagna, A., Giardina, I., Parisi, G., & Silvestri, E. (2012). Spatially balanced topological interaction grants optimal cohesion in flocking models. *Interface Focus*, *2*(6), 715–725. https://doi.org/10.1098/rsfs.2012.0026

Celikkanat, H. Optimization of felf-organized flocking of a robot swarm via evolutionary strategies. In: *2008 23rd international symposium on computer and information sciences*. 2008, 1–6. https://doi.org/10.1109/ISCIS.2008.4717880.

Dave, A., & Malikopoulos, A. A. (2019). Decentralized stochastic control in partially nested information structures. *IFAC-PapersOnLine*, *52*(20), 97–102. https://doi.org/10.1016/j.ifacol.2019.12.134

Dave, A., & Malikopoulos, A. A. Structural results for decentralized stochastic control with a word-of-mouth communication. In: *2020 american control conference (ACC)*. 2020, 1–6. https://doi.org/10.23919/ACC45564.2020.9148046.

Egerstedt, M., Pauli, J. N., Notomista, G., & Hutchinson, S. (2018). Robot ecology: Constraint-based control design for long duration autonomy. *Annual Reviews in Control*, *46*, 1–7. https://doi.org/10.1016/j.arcontrol.2018.09.006

Fine, B., & Shell, D. (2013). Unifying microscopic flocking motion models for virtual, robotic, and biological flock members. *Autonomous Robots*, *35*(2-3), 195–219. https://doi.org/10.1007/s10514-013-9338-z

Gatt, M. C., Quetting, M., Cheng, Y., & Wikelski, M. (2020). Dynamic body acceleration increases by 20% during flight ontogeny of greylag geese anser anser. *Journal of Avian Biology*, *51*(2), e02235. https://doi.org/10.1111/jav.02235

Genter, K. (2017). *Fly with me : Algorithms and methods for influencing a flock* (Doctoral dissertation). The University of Texas at Austin.

Hayes, A., & Dormiani-Tabatabaei, P. Self-organized flocking with agent failure: Off-line optimization and demonstration with real robots. In: *Proceedings 2002 IEEE international conference on robotics and automation (cat. no.02ch37292)*. 2002, 1–6. https://doi.org/10.1109/ROBOT.2002.1014331.

Ibuki, T., Wilson, S., Yamauchi, J., Fujita, M., & Egerstedt, M. (2020). Optimization-based distributed flocking control for multiple rigid bodies. *IEEE Robotics and Automation Letters*, *5*(2), 1891–1898. https://doi.org/10.1109/LRA.2020.2969950

Jafari, M., Xu, H., & Carrillo, L. R. G. (2020). A biologically-inspired reinforcement learning based intelligent distributed flocking control for multi-agent systems in presence of uncertain system and dynamic environment. *IFAC Journal of Systems*

ISSN 1692-8407

and Control, *13*, 100096. https://doi.org/10.1016/j.ifacsc.2020.100096

Kölzsch, A., Flack, A., Müskens, G. J. D. M., Kruckenberg, H., Glazov, P., & Wikelski, M. (2020). Goose parents lead migration v. *Journal of Avian Biology*, *51*(3), e02392. https://doi.org/10.1111/jav.02392

La, H. M., Lim, R., & Sheng, W. (2015). Multirobot cooperative learning for predator avoidance. *IEEE Transactions on Control Systems Technology*, *23*(1), 52–63. https://doi.org/10.1109/TCST.2014.2312392

La, H. M., Nguyen, T. H., Nguyen, C. H., & Nguyen, H. N. Optimal flocking control for a mobile sensor network based a moving target tracking. In: *2009 IEEE international conference on systems, man and cybernetics*. 2009, 1–6. https://doi.org/10.1109/ICSMC.2009.5346069.

Makiguchi, M., & Inoue, J. Anisotropy measurement in artificial flockings: How does one design the optimal boids by evolutionary computation? In: *1st international conference on soft computing and intelligent systems and 11th international symposium on advanced intelligent systems*. 2010, 1–6.

Martínez, F., & Delgado, J. (2012). Wireless visual sensor network robots - based for the emulation of collective behavior. *Tecnura*, *16*(31), 10–18.

Martínez, F., Jacinto, E., & Acero, D. Brownian motion as exploration strategy for autonomous swarm robots. In: *2012 IEEE international conference on robotics and biomimetics (ROBIO)*. 2012, 2375–2380. https://doi.org/10.1109/ROBIO.2012.6491325.

Martínez, F., Rendón, A., & Arbulú, M. (2018). An algorithm based on the bacterial swarm and its application in autonomous navigation problems. *Lecture notes in computer science* (pp. 304–313). Springer International Publishing. https://doi.org/10.1007/978-3-319-93815-8_30

Mirzaeinia, A., Hassanalian, M., Lee, K., & Mirzaeinia, M. (2019). Energy conservation of v-shaped swarming fixed-wing drones through position reconfiguration. *Aerospace Science and Technology*, *94*(1), 105398. https://doi.org/10.1016/j.ast.2019.105398

Morgan, D., Subramanian, G. P., Chung, S.-J., & Hadaegh, F. Y. (2016). Swarm assignment and trajectory optimization using variable-swarm, distributed auction assignment and sequential convex programming. *The International Journal of Robotics Research*, *35*(10), 1261–1285. https://doi.org/10.1177/0278364916632065

Morihiro, K., Isokawa, T., Nishimura, H., & Matsui, N. Characteristics of flocking behavior model by reinforcement learning scheme. In: *2006 SICE-ICASE international joint conference*. 2006, 1–6. https://doi.org/10.1109/SICE.2006.315087.

Morihiro, K., Isokawa, T., Nishimura, H., & Matsui, N. Emergence of flocking behavior based on reinforcement learning. In: *Lecture notes in computer science*. 2006, 699–706. https://doi.org/10.1007/11893011_89.

Nathan, A., & Barbosa, V. C. (2008). V-like formations in flocks of artificial birds. *Artificial Life*, *14*(2), 179–188. https://doi.org/10.1162/artl.2008.14.2.179

Navarro, I., Mario, E. D., & Martino, A. Distributed vs. centralized particle swarm optimization for learning flocking behaviors. In: *European conference on artificial life 2015*. 2015, 1–6. https://doi.org/10.7551/978-0-262-33027-5-ch056.

Nayyar, A., Mahajan, A., & Teneketzis, D. (2013). Decentralized stochastic control with partial history sharing: A common information approach. *IEEE Transactions on Automatic Control*, *58*(7), 1644–1658. https://doi.org/10.1109/TAC.2013.2239000

Oh, H., Shirazi, A., Sun, C., & Jin, Y. (2017). Bio-inspired self-organising multi-robot pattern formation: A review. *Robotics and Autonomous Systems*, *91*, 83–100. https://doi.org/10.1016/j.robot.2016.12.006

Olfati-Saber, R. (2006). Flocking for multi-agent dynamic systems: Algorithms and theory. *IEEE Transactions on Automatic Control*, *51*(3), 401–420. https://doi.org/10.1109/TAC.2005.864190

Ouvrard, T., Groslambert, A., Ravier, G., Grosprêtre, S., Gimenez, P., & Grappe, F. (2018). Mechanisms of performance improvements due to a leading teammate during uphill cycling. *International Journal of Sports Physiology and Performance*, *13*(9), 1215–1222. https://doi.org/10.1123/ijspp.2017-0878

Qiu, H., & Duan, H. (2020). A multi-objective pigeon-inspired optimization approach to UAV distributed flocking among obstacles. *Information Sciences*, *509*, 515–529. https://doi.org/10.1016/j.ins.2018.06.061

Reynolds, C. (1987). Flocks, herds and schools: A distributed behavioral model. *Computer Graphics*, *24*(1), 25–34.

Sankey, D., & Portugal, S. (2019). When flocking is costly: Reduced cluster-flock density over long-duration flight in pigeons. *The Science of Nature*, *106*(7-8), 1–5. https://doi.org/10.1007/s00114-019-1641-x

Semnani, S., & Basir, O. (2017). Multi-target engagement in complex mobile surveillance sensor networks.

Unmanned Systems, *05*(01), 31–43. https://doi.org/10.1142/S2301385017500030

Song, Z., Lipinski, D., & Mohseni, K. (2017). Multi-vehicle cooperation and nearly fuel-optimal flock guidance in strong background flows. *Ocean Engineering*, *141*(1), 388–404. https://doi.org/10.1016/j.oceaneng.2017.06.024

Vásárhelyi, G., Virágh, C., Somorjai, G., Nepusz, T., Eiben, A. E., & Vicsek, T. (2018). Optimized flocking of autonomous drones in confined environments. *Science Robotics*, *3*(20), 1–6. https://doi.org/10.1126/scirobotics.aat3536

Vatankhah, R., Etemadi, S., Honarvar, M., Alasty, A., Boroushaki, M., & Vossoughi, G. Online velocity optimization of robotic swarm flocking using particle swarm optimization (PSO) method. In: *2009 6th international symposium on mechatronics and its applications*. 2009, 1–6. https://doi.org/10.1109/ISMA.2009.5164776.

Veitch, C., Render, D., & Aravind, A. Ergodic flocking. In: *2019 IEEE/RSJ international conference on intelligent robots and systems (IROS)*. 2019, 1–6. https://doi.org/10.1109/IROS40897.2019.8968265.

Wang, C., Wang, J., & Zhang, X. A DEEP REINFORCEMENT LEARNING APPROACH TO FLOCKING AND NAVIGATION OF UAVS IN LARGE-SCALE COMPLEX ENVIRONMENTS. In: *2018 IEEE global conference on signal and information processing (GlobalSIP)*. 2018, 1–6. https://doi.org/10.1109/GlobalSIP.2018.8646428.

Wang, W., Zheng, Y., Lin, G., Zhang, L., & Han, Z. (2020). Swarm robotics: A review. *Jiqiren/Robot*, *42*(2), 232–256. https://doi.org/10.13973/j.cnki.robot.190009

Wilson, S., Glotfelter, P., Wang, L., Mayya, S., Notomista, G., Mote, M., & Egerstedt, M. (2020). The robotarium: Globally impactful opportunities, challenges, and lessons learned in remote-access, distributed control of multirobot systems. *IEEE Control Systems*, *40*(1), 26–44. https://doi.org/10.1109/MCS.2019.2949973

Xiao, Y., Zhang, L., Jin, X., & Kong, Z. (2018). Event-triggered flocking control of mas and its application in maintaining of power line communication system. *IPPTA: Quarterly Journal of Indian Pulp and Paper Technical Association*, *30*(4), 231–240.

Xu, H., & Carrillo, L. R. G. (2017). Fast reinforcement learning based distributed optimal flocking control and network co-design for uncertain networked multi-UAV system (R. E. Karlsen, D. W. Gage, C. M. Shoemaker, & H. G. Nguyen, Eds.). *Unmanned Systems Technology XIX*, *10195*(1), 1–6. https://doi.org/10.1117/12.2262877

Yang, J., Wang, X., & Bauer, P. (2018). Line and v-shape formation based distributed processing for robotic swarms. *Sensors*, *18*(8), 2543. https://doi.org/10.3390/s18082543

Yang, J., Grosu, R., Smolka, S. A., & Tiwari, A. Love thy neighbor: V-formation as a problem of model predictive control (invited paper). In: *27th international conference on concurrency theory (concur 2016)*. 2016, 4:1–4:5. https://doi.org/10.4230/LIPIcs.CONCUR.2016.4.

Yuan, Q., Zhan, J., & Li, X. (2017). Outdoor flocking of quadcopter drones with decentralized model predictive control. *ISA Transactions*, *71*, 84–92. https://doi.org/10.1016/j.isatra.2017.07.005

Yuan, W., Ganganath, N., Cheng, C., Qing, G., Lau, F., & Zhao, Y. (2020). Path-planning-enabled semiflocking control for multitarget monitoring in mobile sensor networks. *IEEE Transactions on Industrial Informatics*, *16*(7), 4778–4787. https://doi.org/10.1109/TII.2019.2959330

Zhang, H.-T., Chen, M., Stan, G.-B., Zhou, T., & Maciejowski, J. (2008). Collective behavior coordination with predictive mechanisms. *IEEE Circuits and Systems Magazine*, *8*(3), 67–85. https://doi.org/10.1109/MCAS.2008.928446

Zhu, B., Xie, L., & Han, D. Recent developments in control and optimization of swarm systems: A brief survey. In: *2016 12th IEEE international conference on control and automation (ICCA)*. 2016, 1–6. https://doi.org/10.1109/ICCA.2016.7505246.

Tekhnê
January - June 2021, Vol. 18, No. 1, pp. 21 – 36

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Temperature control system for a hatchery

Sistema para el control de temperatura de una incubadora de huevos de gallina

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A closed-loop PID controller tuning method is presented, as well as a control mechanism that functions as an egg incubator controller to control the temperature. The method's performance is compared using digital simulation tests, and the PID controller gains are determined based on the system requirements. Finally, recommendations for using the tested method as well as arguments for why we reject other methods are provided.

Keywords: Control, incubator, PID, temperature, transfer function

Se presenta un método de sintonización de controladores PID de lazo cerrado, un mecanismo de control que opera como regulador de una incubadora de huevos, el cual controla la temperatura. Mediante pruebas de simulación digital se compara el desempeño del método y se determinará las ganancias del controlador PID según los requerimientos del sistema. Finalmente, se ofrecen recomendaciones sobre la utilización del método probado y los argumentos por los cuales descartamos otros métodos.

Palabras clave: Control, función de transferencia, incubadora, PID, temperatura

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Introduction

Poultry production is growing in Colombia, as the consumption of chicken meat and eggs has been increasing for a long time (Páramo et al., 2020). They have become an important source of food for humans, providing higher quality proteins, offering a wide range of amino acids and essential minerals that benefit physical development (Blanco & Ramos, 2019; Zutta, 2005). The high demand for these products has led to the fact that natural reproduction is not enough, therefore, it has been necessary to use artificial incubators to increase production (Millette et al., 2020). Poultry breeding is a meticulous process, full of details and very strict parameters that must be controlled for the eggs to be successful (Marçal et al., 2015).

The control parameters to be taken into account in an artificial incubator are temperature, ventilation, turning, and humidity of the environment (Guzmán & Ramírez, 2017; Santoso et al., 2020). These parameters or physical variables will be controlled by a control design and verified by the simulation to satisfy the optimal breeding characteristics (Bello et al., 2013). Making an egg incubator that is efficient and inexpensive is a challenge because egg embryos are very fragile, and any sudden change in temperature or humidity can significantly affect chick growth and time to hatch ("Diseño e implementación de una incubadora de huevos con aire forzado basada en microcontrolador," n.d.).

Within the industry three types of temperature controls are generally known, ON-OFF, which work according to their name, it turns on and off continuously to maintain the exact desired temperature set point (Che et al., 2019; Khera & Kohli, 2018). When the temperature exceeds the set point it turns off and when the temperature is below the set point it turns on. Proportional controllers reduce the power of the heater when it detects that the temperature will exceed the setpoint, maintaining a stable temperature and fast response, but may exhibit oscillations in the controlled variable or present error in steady-state, and PID controllers offer proportional, integral, and derivative control, is feedback control to make the error between the output and input is zero, compensates for temperature changes thanks to its combination and can adjust each variable, making it more accurate (López, 2014).

Of the controller types, the most suitable for incubator temperature control is the PID controller which is the most susceptible to changes and can react quickly to compensate for them (Kapen et al., 2020). In addition, it can predict any change or effect on the output, thanks to its derivative function. Currently, they have already realized temperature control systems for hatcheries, for example, Microcontroller-based controls have been used that can control temperature, humidity, and reverse eggs automatically and through the Internet of Things (IoT) system help farmers to monitor the hatchery in real-time and remotely (Farfán et al., 2011; Sanjaya et al., 2018).

Microcontrollers have also been used that have been designed using fuzzy control, which is about logically determining what process to do to achieve the control objectives from a basis provided by the designer (Colmenares et al., 2003). This controls the egg position, temperature, and humidity of the incubator and ensures the best conditions for different types of eggs. Next is to build an IoT system to control the incubator remotely (Aldair et al., 2018). Finally, a study was conducted using Arduino IDE Software and Matlab 2015a to simulate and operate a PID system that would be used, as well as design the plant that would produce a temperature response in the hatching of the egg in the incubator (Shafiudin & Kholis, 2018).

Problem statement

The starting point for this project is an already implemented incubator from which 18 temperature data are obtained from a transient response test by feeding the resistance and measuring the behavior of the temperature concerning time. It is desired to design a control system to maintain the temperature of the artificial incubator because if it varies, it can alter the growth of the embryo.

In the data obtained in the test, an increase in temperature is observed after 1 minute, reaching 48.0 degrees Celsius, when the ideal temperature for incubation is 37.5 degrees Celsius, this behavior is because it is an open-loop control. If this temperature is maintained in the egg incubator, poultry production will be affected by the loss of eggs or faster development, altering the growth of the embryo and thus affecting the quality of the chick.

The incubator currently implemented has a heating element, a temperature sensor, and a fan to ensure the movement of hot air inside the incubator. The heating of the eggs is produced by the heat exchange between the air and the eggs, therefore the air temperature is a fundamental factor in the process so the main objective is to design an automaton device that controls in a closed-loop the temperature and feeds back the input with the previous output, ensuring the proper control of temperature to be maintained at 37.5 degrees Celsius inside the egg incubator and that despite external disturbances the control responds quickly and stabilizes the temperature. The system would have the behavior shown in Fig. 1.

Methods

The design of the control system for the hen egg incubator will be based on the data obtained in the transient response test in which the temperature behavior concerning time was obtained as shown in Table 1 (Torres & Ramírez, 2012). These data were captured in the laboratory directly from the incubator understudy, and calibrated measuring equipment

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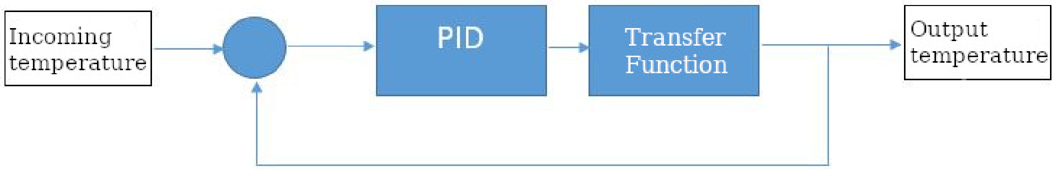
Figure 1

Block diagram of the control system.



was used. Although they correspond to a single reading, multiple tests have been carried out on this plant, and it has been found that the behavior does not show significant variations (Lata et al., 2020; Maasoum et al., 2020).

Table 1

Table of laboratory data

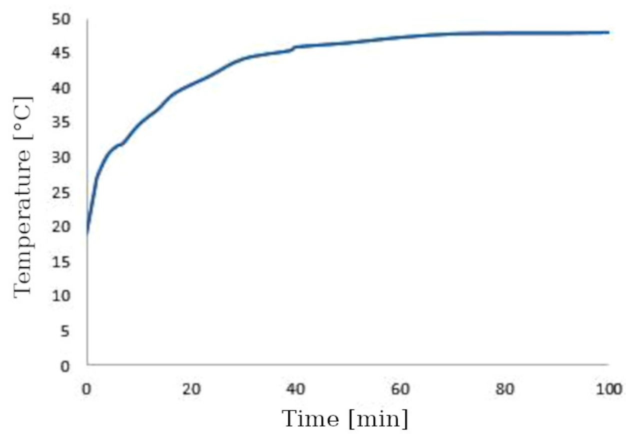
Time [minutes]	Temperature [Degrees]
0	19
1,6	25.7
2	27.1
4	30.3
6	31.7
7	32.0
10	34.7
13,5	36.8
14,16	37.3
17	39.3
23,5	41.7
30	44.2
39	45.4
40	45.9
50	46.5
60	47.3
70	47.8
80	47,9
90	47.9
100	48.0

From these data the following procedures will be done for the design of the closed-loop controller:

1. Obtain the real temperature behavior of the incubator by graphing the data obtained in the test.
2. Based on the obtained graph, find the mathematical function that describes the behavior of the incubator.

Figure 2

Graph of real behavior.



3. Validate the behavior of the model.
4. Find the transfer function.
5. Perform the stability analysis and find the interval of K in which the system is stable.
6. Evaluation of PID controller method. This requires a study of existing tuning strategies.
7. Perform the simulation of the design using the Root Locus function of MATLAB.
8. External disturbance test.
9. Analyze the results of the model.

Development procedure

Incubator temperature behavior

The first analysis of the data is carried out graphically by means of a representation of the laboratory test. Fig. 2 shows the actual temperature behavior of the egg incubator.

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Mathematical function

The behavior of the curve resembles a first-degree transfer function. The canonical equation has the following form:

$$y(t) = K - K * e^{\left(-\frac{t}{\tau}\right)} \tag{1}$$

$$y(t) = K + (K - C.initial) * e^{\left(-\frac{t}{\tau}\right)} \tag{2}$$

$$K = 48 \tag{3}$$

With the values in the table, we will find the equation that simulates the behavior of the incubator, making a linear regression to find the time value that corresponds to 63 percent of K. That is, we will obtain the time in minutes for a temperature of 37.27 degrees. We will perform the linear regression between the times of 13.5 and 17 minutes.

$$m = \frac{39.3 - 36.8}{17 - 13.5} \tag{4}$$

$$m = 0.714 \tag{5}$$

$$b = 36.8 - 0.714 * 13.5 \tag{6}$$

$$Temperature = m * Time + b \tag{7}$$

$$Temperature = 0.714 * Time + 27.16 \tag{8}$$

$$Time = \frac{Temperature - 27.16}{0.714} \tag{9}$$

We only take into account when the exponential form starts.

$$0.63 * (K - 19) = 18.27 \tag{10}$$

$$18.27 + C.initial = 37.3 \tag{11}$$

$$Time = \frac{37.3 - 27.16}{0.714} \tag{12}$$

$$Time = 14.2 = \tau \tag{13}$$

Finally, the resulting equation is as follows:

$$Temperature(t) = 48 - 29 * e^{\left(-\frac{t}{14.2}\right)} \tag{14}$$

$$Temperature(\infty) = 48 = K \tag{15}$$

$$Temperature(0) = 19 = C.initial \tag{16}$$

A canonical equation that simulates the behavior of the egg incubator is obtained by verifying the important points. The two graphs are compared to see if this is true. Fig. 3 shows the behavior of both curves, the blue one was obtained from the incubator data sample and the orange one was obtained using the canonical equation found, it is concluded that the canonical equation corresponds to the real behavior of the incubator since both graphs are similar. From the equation, the transfer function of the system is found.

Transfer function

The Laplace transform is applied to the canonical equation to obtain the closed-loop transfer function.

$$Laplace\{48 - 29 * e^{\left(-\frac{t}{14.2}\right)}\} \tag{17}$$

$$Output(s) = \frac{19(s + 0.1779)}{s(s + 0.0704)} \tag{18}$$

Finally, taking into account the unit step of the input the transfer function that simulates the behavior of the data obtained in the laboratory is:

$$H(s) = \frac{19(s + 0.1779)}{(s + 0.0704)} \tag{19}$$

Stability analysis

Fig. 4 shows the structure of the entire system including the PID controller.

Simplifying by block algebra.

$$G(s) = \frac{K19(S + 0.1779)}{S + 0.0704} \tag{20}$$

$$H(s) = 1 \tag{21}$$

$$\frac{G(s)}{1 - G(s) * H(s)} \tag{22}$$

$$\frac{G(s)}{1 + \frac{K19(S+0.1779)}{S+0.0704}} \tag{23}$$

$$\frac{\frac{K19(S+0.1779)}{S+0.0704}}{\frac{S+0.0704+K19(S+0.1779)}{S+0.0704}} \tag{24}$$

$$\frac{K19(S + 0.1779)}{S + 0.0704 + K19(S + 0.1779)} \tag{25}$$

$$\frac{C(s)}{\mu(s)} = \frac{K19(S + 0.1779)}{(K19 + 1)S + 0.1779(K19 + 0.395728)} \tag{26}$$

$$\frac{C(s)}{\mu(s)} = \frac{K19(S + 0.1779)}{(K19 + 1)S + 0.1779(K19 + 0.395728)} \tag{27}$$

Figure 3

Real vs. simulated behavior comparison.

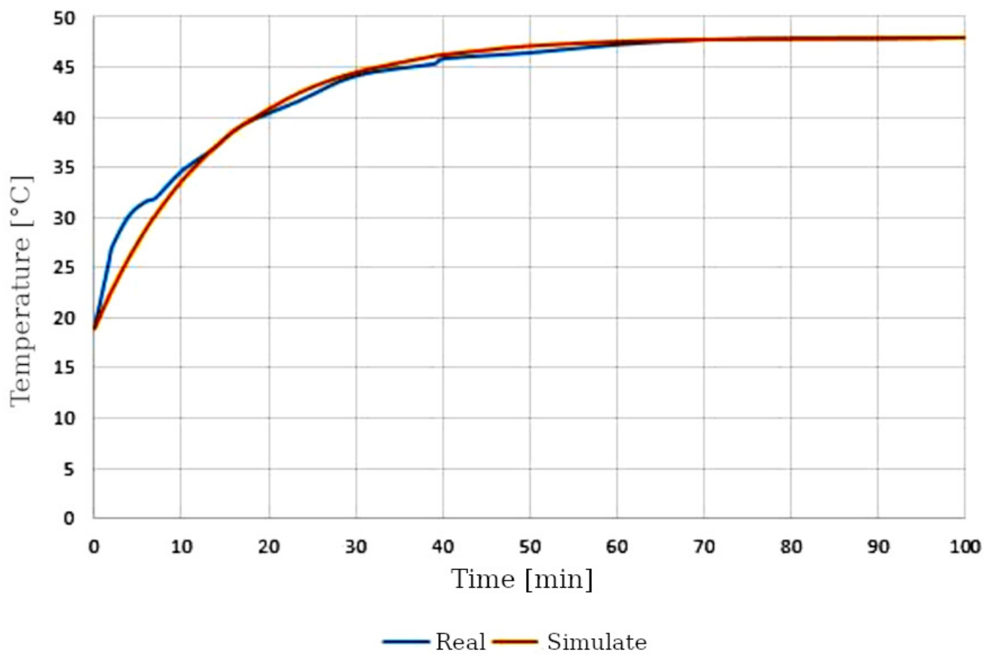
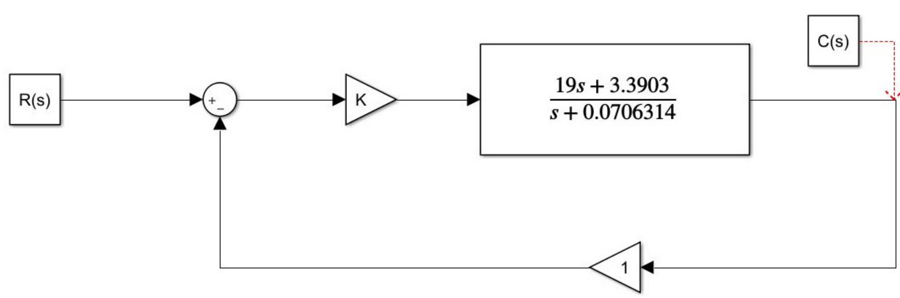


Figure 4

Closed-loop system model.



$$(19K + 1)S + 3.3801K + 0.0704 = 0 \tag{28}$$

$$\begin{aligned} S1 &= (19K + 1) \\ S0 &= 3.3801K + 0.0704 \end{aligned} \tag{29}$$

Case 1:

$$19K + 1 > 0 \tag{30}$$

$$19K > -1 \tag{31}$$

$$K > -\frac{1}{19} \tag{32}$$

$$\underbrace{K > -0.052} \tag{33}$$

Case 1:

$$3.3801K + 0.0704 > 0 \tag{34}$$

$$3.3801K > -0.0704 \tag{35}$$

ISSN 1692-8407

$$K > -\frac{0.0704}{3.3801} \tag{36}$$

$$\underbrace{K > -0.0208} \tag{37}$$

Therefore, for the system to be stable:

$$K > 0 \tag{38}$$

PID controller method evaluation

The control system to be implemented is as shown in Fig. 5.

Therefore:

$$\frac{y(s)}{r(s)} = \frac{\left(Kp + \frac{K1}{S} + SKD\right)\left(\frac{19(S+0.1779)}{S+0.0704}\right)}{1+\left(Kp + \frac{K1}{S} + SKD\right)\left(\frac{19(S+0.1779)}{S+0.0704}\right)} \tag{39}$$

$$\frac{y(s)}{r(s)} = \frac{\frac{(KpS+K1+S^2KD)(19(S+0.1779))}{S^2+S0.0704}}{1+\left(\frac{(KpS+K1+S^2KD)(19(S+0.1779))}{S^2+S0.0704}\right)} \tag{40}$$

$$a = \frac{(KpS + K1 + S^2KD)(19(S + 0.1779))}{S^2 + S0.0704} \tag{41}$$

$$\frac{y(s)}{r(s)} = \frac{a}{\frac{S^2+S0.07+(KpS+KI+S^2KD)(19(S+0.1779))}{S^2+S0.0704}} \tag{42}$$

$$b = (KpS + KI + S^2KD)(19(S + 0.1779)) \tag{43}$$

$$\frac{y(s)}{r(s)} = \frac{b}{(S^2 + S0.07 + b)} \tag{44}$$

The following will show some methods for tuning a PID controller. The objective of these methods is to calculate the gains of our PID controller or the individual cases, i.e. proportional only Proportional and integral gain (PI), proportional and derivative gain (PD), or proportional integral and derivative (PID).

Results

Ziegler-Nichols method

The Ziegler-Nichols method allows practically tuning a PID controller, without the need to know the equations of the plant or the system to be controlled. It is one of the most widely used methods and allows the proportional, integral and derivative gains to be defined from the system output in either open or closed-loop, but is best suited for open-loop systems.

The method consists of replacing the PID controller with a unitary stepper and having a sensor supplying the system output. With the output behavior, we can calculate the parameters of the PID controller. For the article, the Ziegler-Nichols method would not be the best procedure to calculate the PID controller because it is used when the plant equations are not known and it is based only on the output of the system through the reading of a sensor. In the case of the article, we already know the plant equations and we do not have a real-time sensor reading of the output.

The gains of the PID controller are calculated using another method that uses what has already been obtained as the system's transfer function, and it is calculated for a closed-loop system to ensure accuracy. There is an indeterminacy when applying the equations proposed by the Ziegler-Nichols method, for this reason, our system is not suitable to apply this solution method.

Ziegler-Nichols oscillation

In this method, it is not required to remove the PID controller from the closed-loop. This method proposes to take K_i and K_d to 0, and alternate K_p until the system oscillates constantly, at this point it is necessary to measure the proportional gain K_p called critical gain or K_c, and the period of oscillation T_c in minutes. Once these two values are measured, you can calculate the gains of the PID controller or the individual cases, i.e. only proportional and integral gain (PI), proportional and derivative gain (PD), or proportional, integral and derivative (PID).

For our system by taking our gains K_i and K_d to zero and varying K_p in different values we did not obtain any oscillation, therefore the system has no oscillatory response any fundamental parameter for obtaining the critical gain, the reason that our system has no oscillatory response alternating K_p may be because it is linear for any value of K_p.

Root Locus Simulation in MATLAB

Initially the plant transfer function is written and the SISOTOOL function is called which plots the Root Locus (Figs. 6 and 7).

```
H= tf ([19 3.3801], [ 1 0.0704]); sisotool (H)
```

Fig. 6 identifies the Root locus of the plant by locating the zero and the pole, both real on the left side of the complex plane. Being the pole -0.0704 and the zero of -0.1779. Fig. 7 shows the response to the passage of the plant with a proportional controller $K_p = 1$, which has no overshoot and its stabilization time is greater than 60 s, stabilizing at 0.98.

As the proportional control is displaced on the straight line between pole and zero, the step response changes, therefore, this will be the strategy to achieve the type of response expected under the following design parameters:

- Stabilization time < 10 s.
- Overshoot < 5 percent.

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Figure 5

Complete system block diagram.

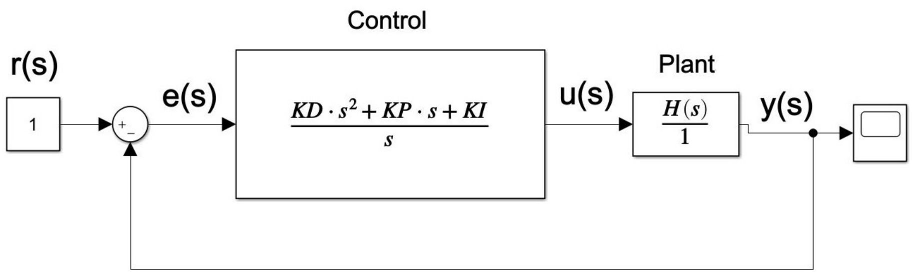

Figure 6

Root Locus plant - System Poles and Zeros.

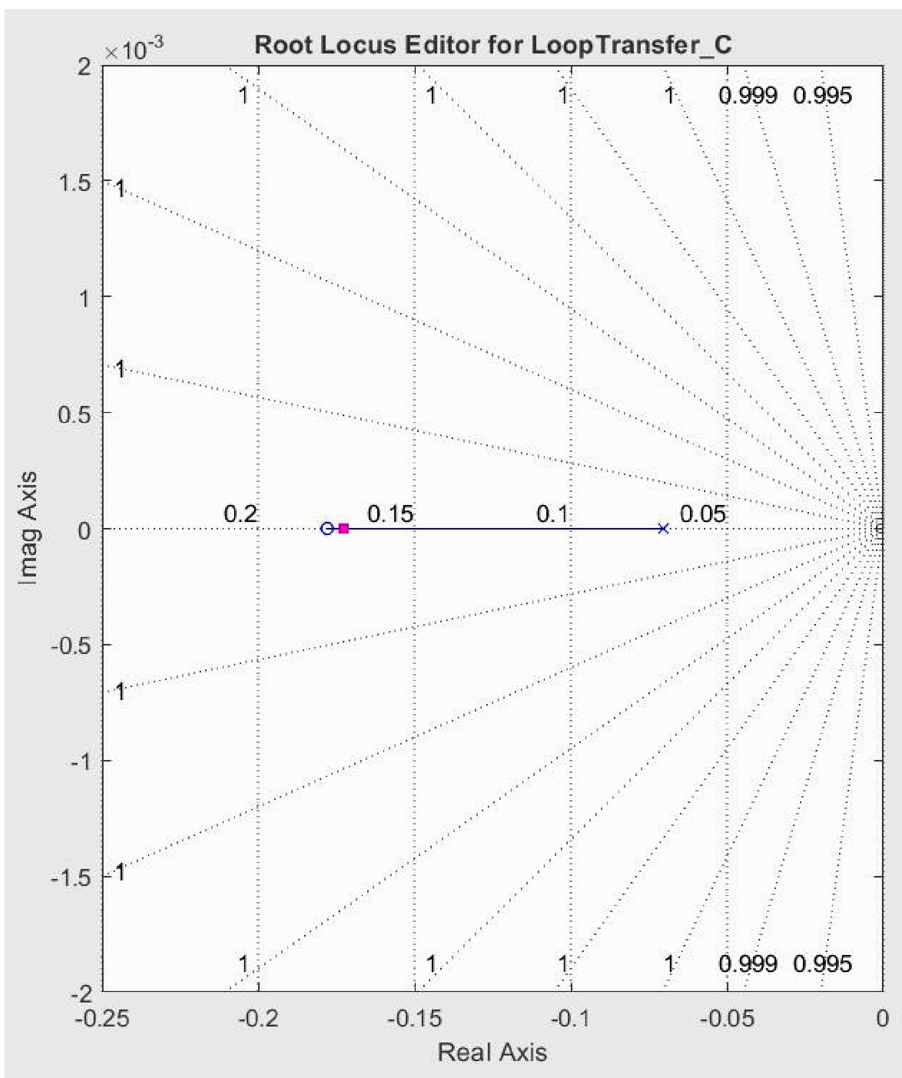

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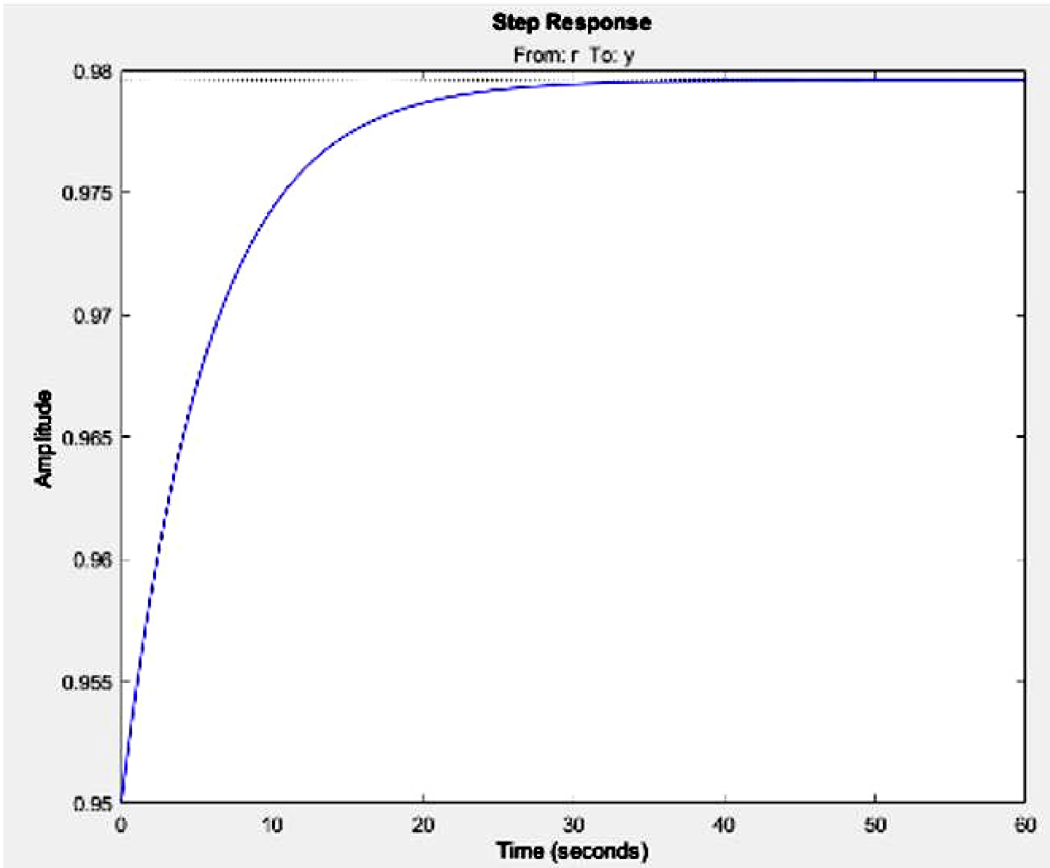
Figure 7

Step response of the system - $K_p = 1$.



- Steady state error $ess = 1$ percent.

In the Root locus, the stabilization and overshoot time parameters were configured to establish the area where the controller should be located and comply with the parameters. Fig. 8 shows the design area. In the step response, the stationary time error is set to 1 percent (Fig. 9).

Since the transfer function provides us with the position of the zeros and poles, it is not sufficient to meet the previously established design criteria since even if the gain of K_p is increased, it always stabilizes in 26 s. To improve the stabilization time, a pole will be included which, together with the proportional controller, generates a PI controller.

In MATLAB an integrator was added with a pole at the origin and a zero at -1, this causes an overshoot of 0.24 percent and a stabilization time of 14 s, a time that does not meet the design criteria. Fig. 10 shows the addition of a pole and a zero, and Fig. 11 shows the response of the controller over time.

To bring the stabilization time to a value that meets the criteria, the controller gain will be moved along the path obtained by Root Locus and if necessary change the poles or zeros over the design zone.

The response that best met the design parameters is stabilized at a time of 9.82 s, with an ess of 1 percent and an overshoot of 2.98 percent, as shown in Fig. 13. To reach this response, the real zero was shifted to -17.5 as shown in Fig. 12 and the gain of the controllers to 0.128, thus obtaining a PI controller with a value of $(0.128\ (\ 1{+}0.054s\ ))/s$, where $K_p = 0.0069$ and $K_i = 0.128$.

It was identified that only by using a controller with proportional and integral part does the system behaves stable, therefore it was not necessary to implement the differential controller. These data were chosen to perform the external disturbance test with the SIMULINK Simulator since it did not allow very large values that also made the system stable and satisfy the design criteria.

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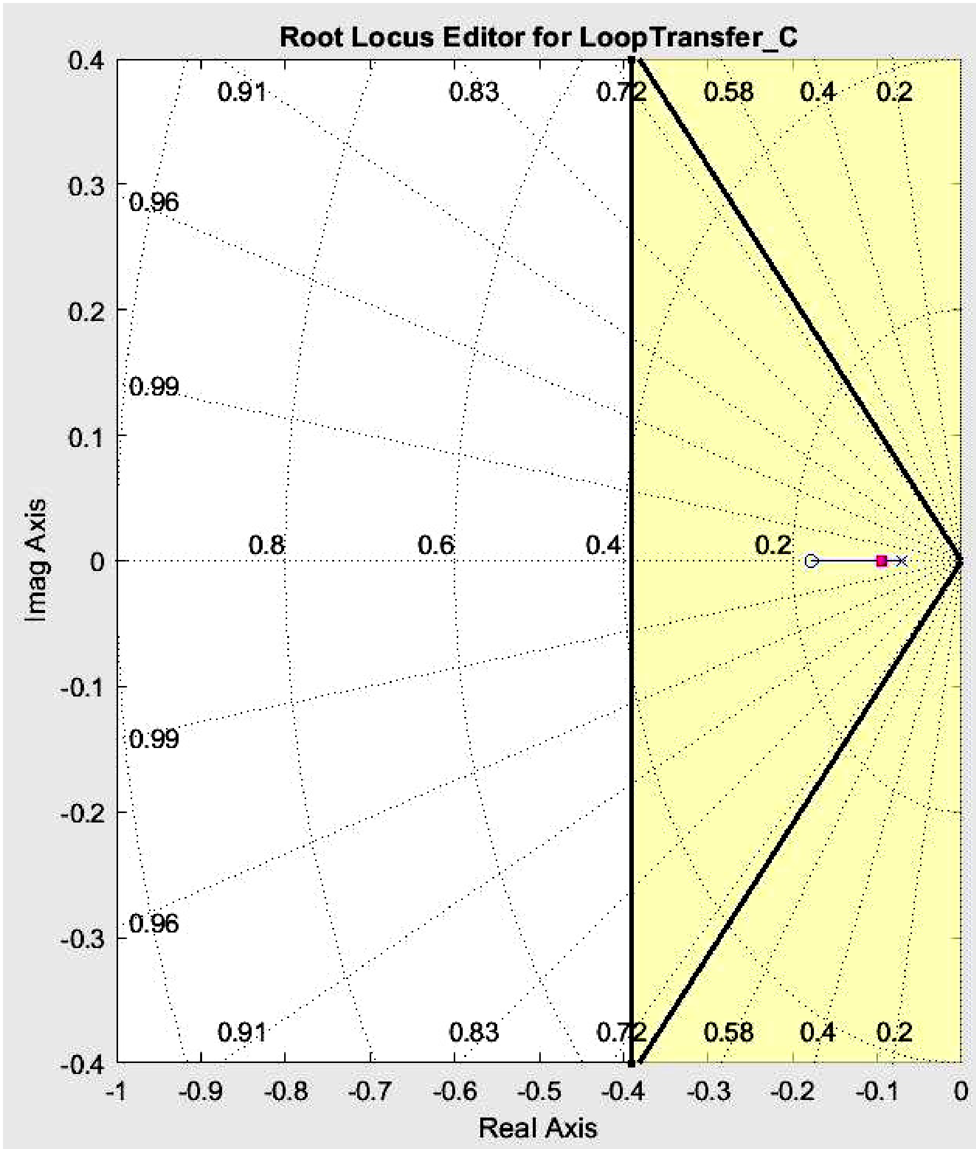
Figure 8

Design area.



To verify the veracity of the results obtained with the MATLAB Simulator, the values of the constants were taken and simulated in Python (Figs. 14 and 15).

External disturbance test

The system's external disturbance test was performed using a 0.5 magnitude pulse with a duration of 3 s and a period of 30 s (Kokieva et al., 2020; Roscoe et al., 2020). This signal type was used to simulate the opening of an incubator door. The circuit was assembled in SIMULINK as shown in Fig. 16. Fig. 17 shows the behavior of the PID controller when tuned with the circuit of Fig. 16.

Fig. 18 shows the response graph to the simulated disturbance, where there is an elevation of 1.039 during the first 3 seconds (pulse duration). After these three seconds the signal decreases to 0.089, begins to stabilize until it reaches the ideal temperature, and takes 6.7s for its complete stabilization. This shows that the designed PI controller corrects the disturbances quickly and stably (Fig. 19).

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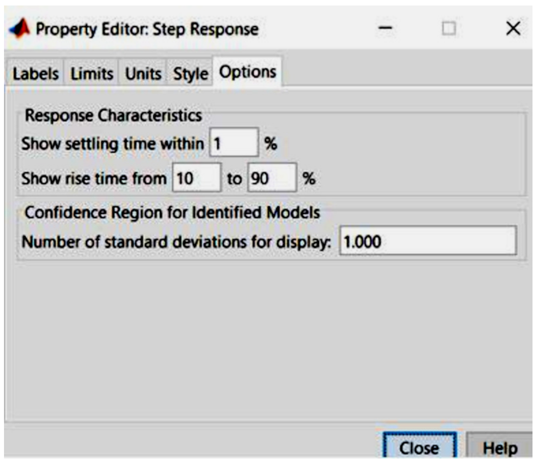
Figure 9

Stationary error.



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Conclusion

Through the development of this experiment, the different possible responses of the system to the different types of controllers are observed, observing the best response when using a PD or PID controller. These, however, must be correctly adjusted to obtain the desired response, since in case of generating an erroneous adjustment, adverse and unforeseen effects can be generated, or in more serious cases, cause the destabilization of the system. An automatic system was implemented to control the temperature of an incubator, managing to maintain a stable temperature, improving the quality of egg production in an artificial incubator. Since the transfer function is of the first order, no matter how much the value of Kp is increased and K_i and K_d are kept at zero, the response of the system will never oscillate, therefore it is not possible to calculate the value of P_c. Different behavior if it were a function of second degree that as K_p increases if it oscillates. The incubator behavior curve has no delay, so it is not possible to use the Ziegler-Nichols reaction curve and Cohen-Coon methods in which the delay time is necessary to find the constants.

For the control of the incubator, a design with a PI controller was implemented since it was identified that the differential controller is not necessary for the system to be stable and to have external disturbance to be able to stabilize the system quickly. Using the MATLAB software with the SISOTOOL tool facilitates the obtaining of the PID controller thanks to the Root locus in which the poles and zeros can be identified quickly with only knowing the plant of the system, in addition, it allows to visualize the graph of the response to the system step and thus to identify the key points of evaluation such as the overshoot, the stationary error, the stability time, the rise time, among others.

The usefulness of using software to obtain the Root Locus is important because it reduces the design time, calculation and prevents errors and attributes more precision and accuracy when obtaining the controller. Although MATLAB gives a possible answer in many cases it does not meet the design requirements, therefore, the designer must modify the data obtained by MATLAB, so that it fits the necessary criteria.

The PID controller is a robust tool, widely known and used at the industrial level, and really powerful to achieve optimal process operation. However, on many occasions the tuning requirements of its parameters are unknown or disregarded, restricting the process to a game of trial and error. These types of exercises, in addition to their industrial applications, provide very useful academic tools for young designers interested in the field, especially now that design tools such as MATLAB and Python are available. It is therefore expected that the results of this article, presented in a practical way, will help develop professionals in the field and help to extend design applications for this important component of control systems.

References

Aldair, A. A., Rashid, A. T., & Mokayef, M. (2018). Design and implementation of intelligent control system for egg incubator based on iot technology. *2018 4th International Conference on Electrical, Electronics and System Engineering (ICEESE)*, 49–54.

Bello, D., García, L., & Martínez, F. (2013). Planta robusta de levitación neumática para investigación y formación en control y visión artificial. *Tekhnê*, *10*(2), 33–41.

Blanco, L., & Ramos, M. (2019). Sustainable diets and meat consumption reduction in emerging economies: Evidence from colombia. *Sustainability*, *11*(23), 6595. https://doi.org/10.3390\/su11236595

Che, A., Muzaffar, A., Shukri, A., Mohd, R., Rozali, S., Mohamad, S., & Hadinata, A. (2019). Analysis of light bulb temperature control for egg incubator design. *International Journal of Integrated Engineering*, *11*(4), 268–276. https://doi.org/10.30880\/ijie.2019.11.04.031

Colmenares, J., Ospino, C., & Vargas, O. (2003). Adecuación y automatización para un horno industrial a gas natural. *Tekhnê*, *1*(1), 24–29.

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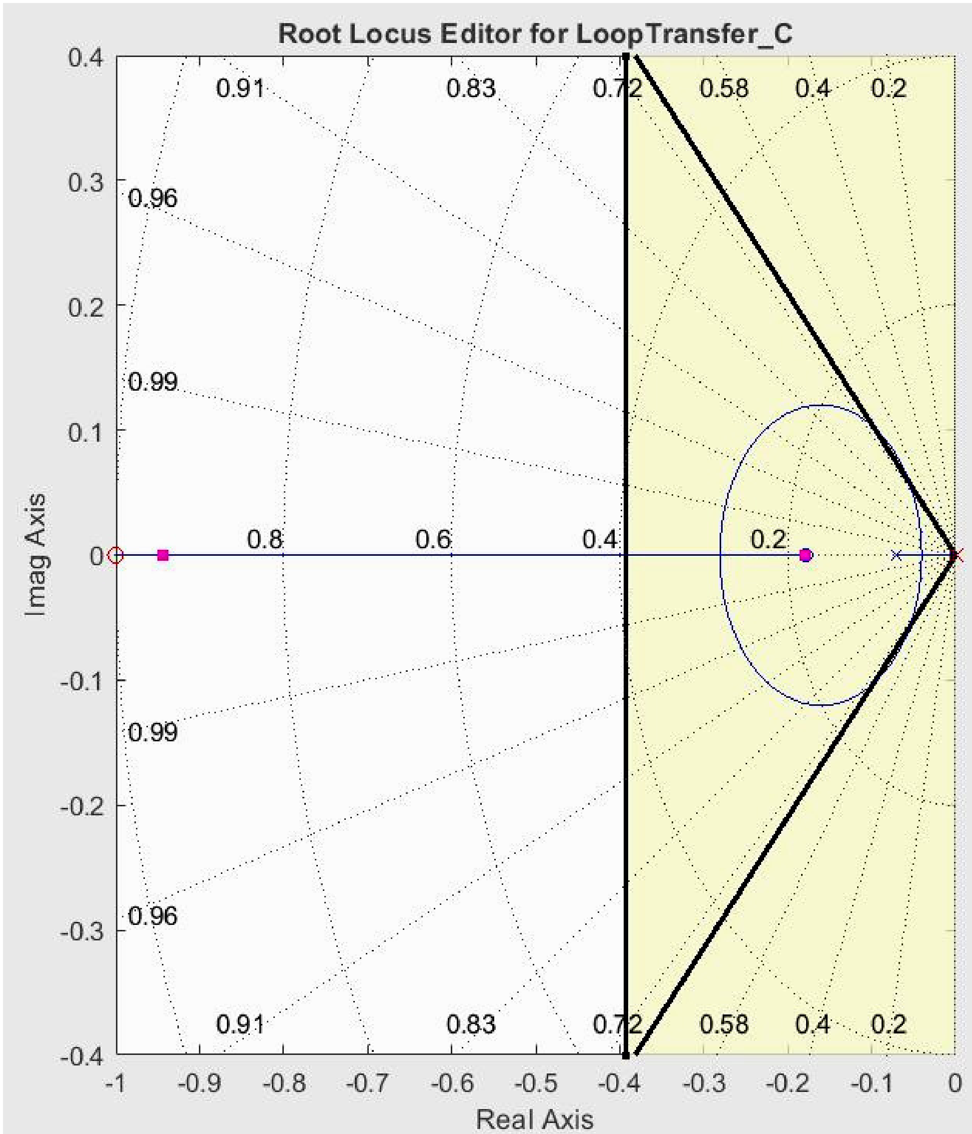
Figure 10

Root Locus PI.



Diseño e implementación de una incubadora de huevos con aire forzado basada en microcontrolador. (n.d.). *2018 Conferencia Internacional sobre Avance en Ingeniería Eléctrica y Electrónica (ICAEEE).*

Farfán, D., Martínez, F., & Pirajan, R. (2011). Development system for atmel microcontroller oriented towards plc. *Tekhnê*, *8*(1), 47–54.

Guzmán, J., & Ramírez, J. (2017). How can concrete be improved through processes that are bio-friendly to the environment and that enhance its construction qualities? *Tekhnê*, *14*(2), 49–58.

Kapen, P. T., Youssoufa, M., Foutse, M., Manfouo, H., & Mbakop, F. O. N. (2020). Design and prototyping of a low-cost, energy efficient eggs incubator in developing countries: A case study of cameroon. *Scientific African*, *10*(1), e00618. https://doi.org/10.1016/j.sciaf.2020.e00618

Khera, N., & Kohli, S. Comparison of fuzzy and on/off controller for winter season egg hatching incubator system. In: *2018 international conference on sustainable energy, electronics, and computing*

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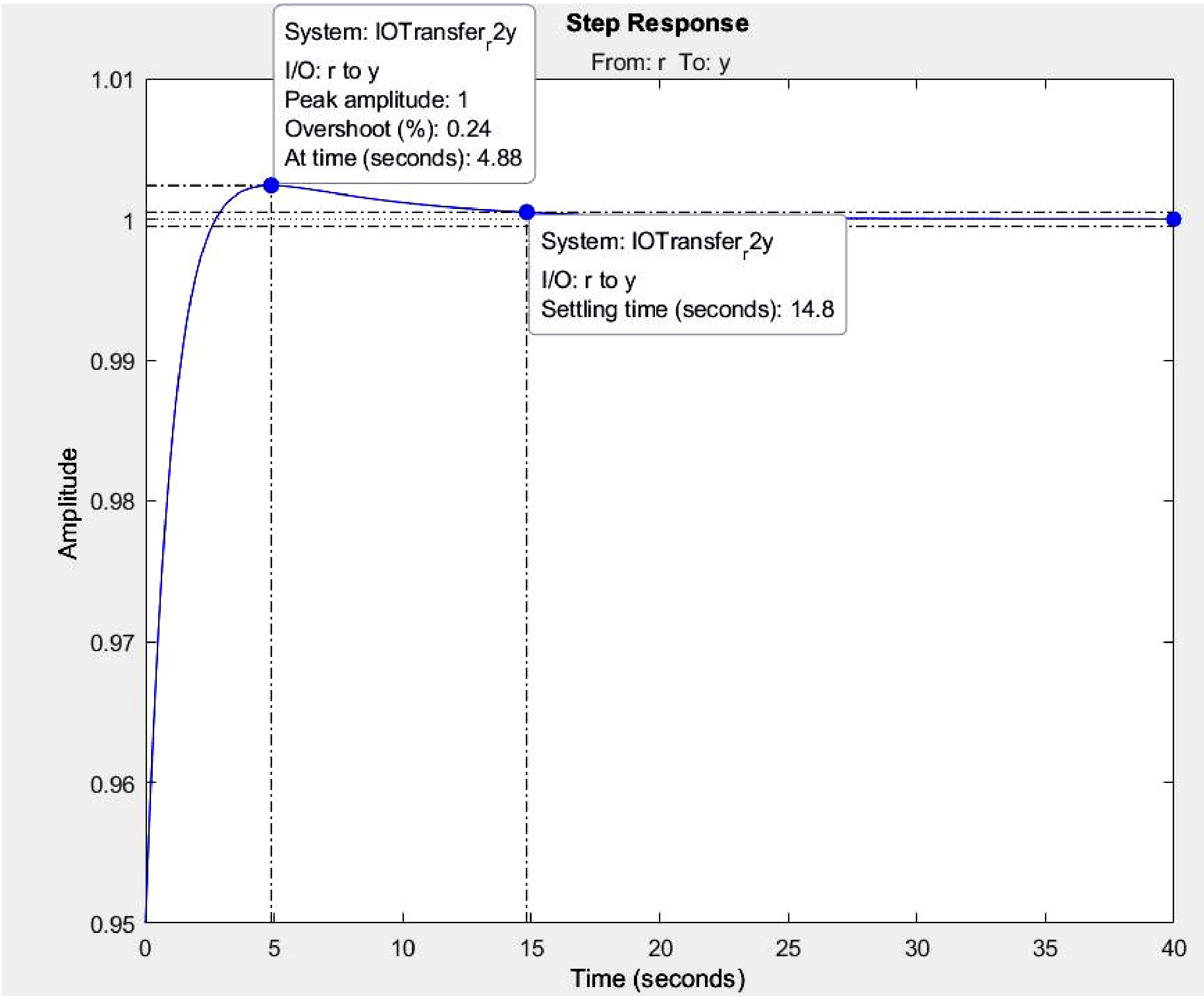
Figure 11

PI controller time response.



systems (SEEMS). 2018, 1–6. https://doi.org/10.1109/SEEMS.2018.8687365.

Kokieva, G. E., Trofimova, V. S., & Fedorov, I. R. Greenhouse microclimate control. In: *Iop conference series: Materials science and engineering*. *1001*. (1). 2020, 012136. https://doi.org/10.1088/1757-899X/1001/1/012136.

Lata, S., Sah, R., Singh, S., & Jaiswal, S. Greenhouse monitoring using wsn and sensenuts nodes. In: *Aip conference proceedings*. *2294*. 2020, 030006. https://doi.org/10.1063/5.0031711.

López, C. (2014). Performance evaluation of two bio-inspired optimization techniques: Genetic algorithms and particle swarm. *Tekhnê*, *11*(1), 49–58.

Maasoum, S. M. H., Mostafavi, A., & Sadighi, A. An autoencoder-based algorithm for fault detection of rotating machines, suitable for online learning and standalone applications. In: *2020 6th iranian conference on signal processing and intelligent systems (ICSPIS)*. 2020, 1–6. https://doi.org/10.1109\/ICSPIS51611.2020.9349574.

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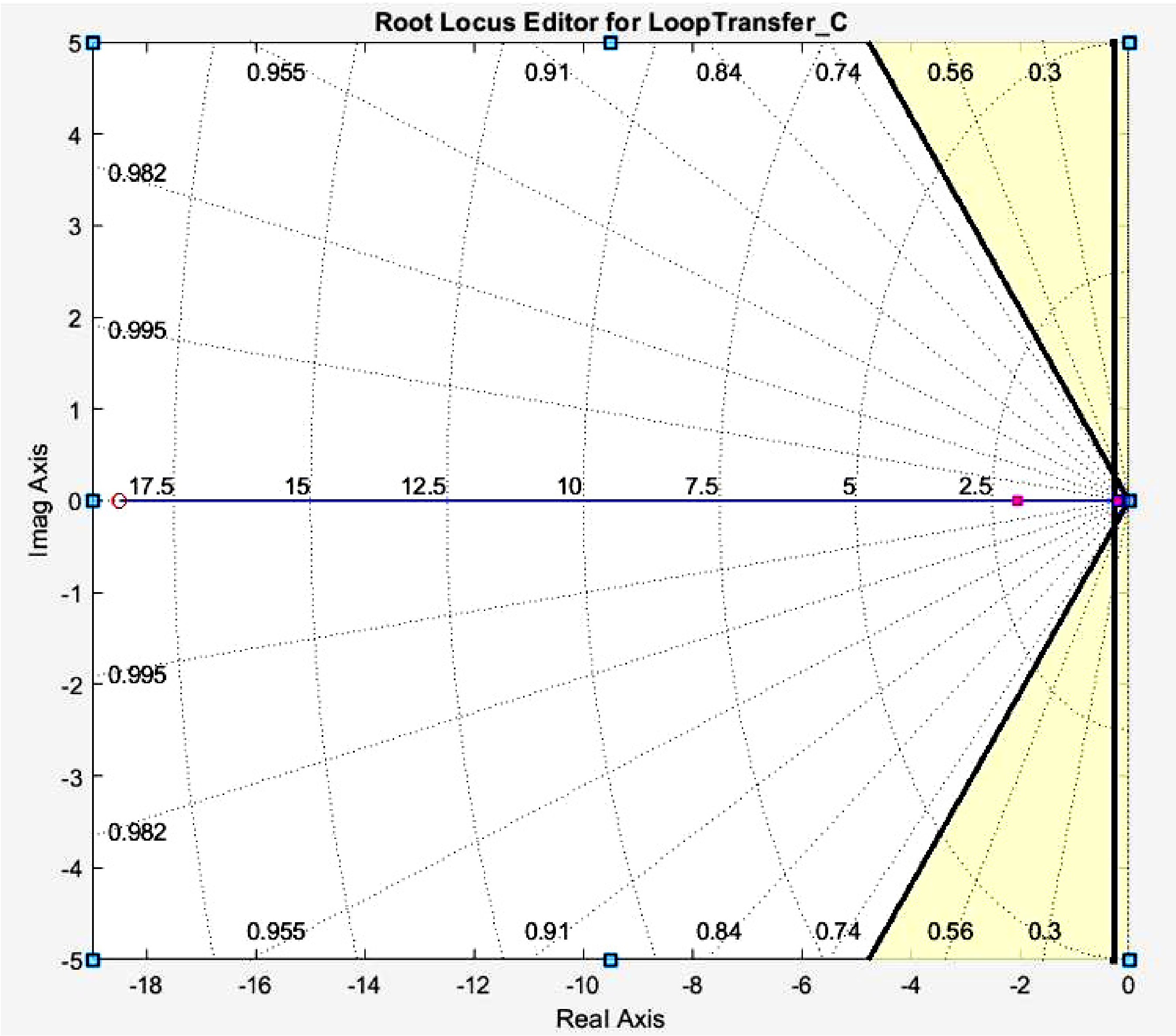
Figure 12

System PI controller.



Marçal, T., Antunes, B., Ferreira, R., Correia, C., Pires, D., Matos, A., & Simões, J. N. (2015). Wireless multi-physiological signal monitor for clinical discharge and readmissions criteria setting and ambulatory usage. *2015 IEEE 4th Portuguese Meeting on Bioengineering (ENBENG)*, 1–6.

Millette, S., Hull, C. E., & Williams, E. (2020). Business incubators as effective tools for driving circular economy. *Journal of Cleaner Production*, *266*(1), 121999. https://doi.org/10.1016/j.jclepro.2020.121999

Páramo, M., Romero, M., & Wilches, F. (2020). International journal of engineering research and technology. *International Journal of Engineering Research and Technology*, *13*(11), 4004–4010.

Roscoe, A., Knueppel, T., Silva, R. D., Brogan, P., Gutierrez, I., Elliott, D., & Campion, J.-C. P. (2020). Response of a grid forming wind farm to system events, and the impact of external and internal damping. *IET*

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Figure 13

Time response of the plant PI controller.

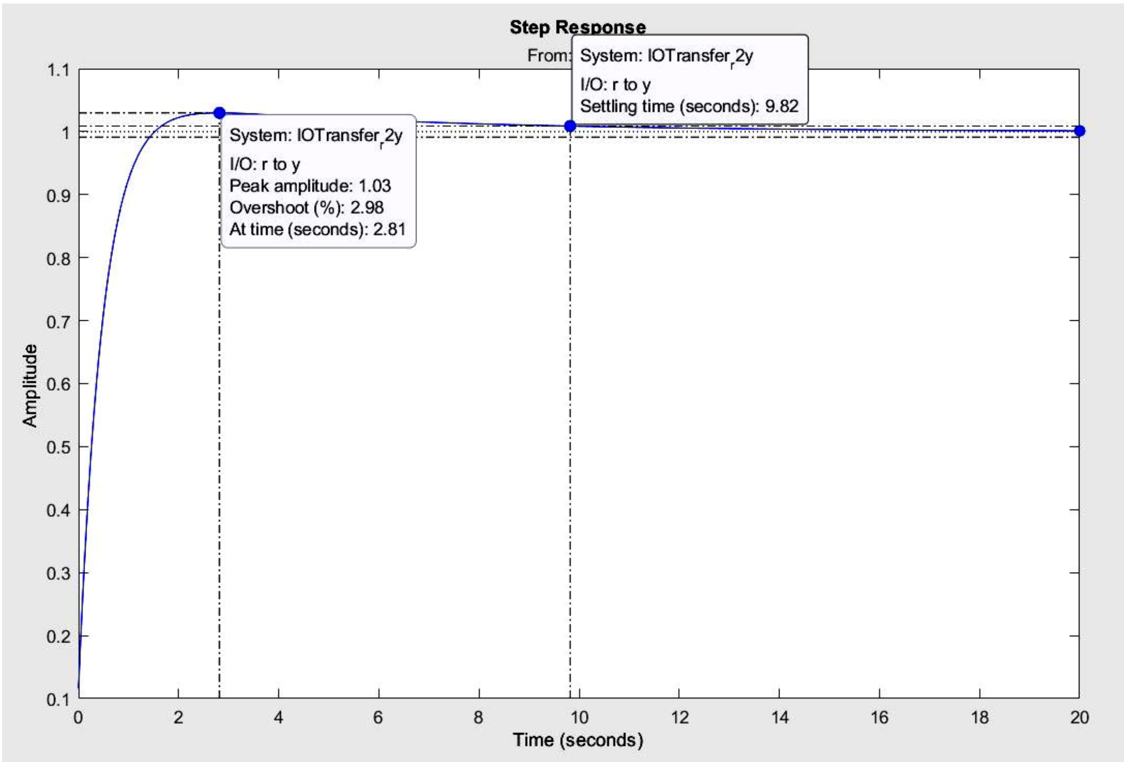


Figure 14

Python simulation code.

```
import numpy as np
Kp = 0.0069
Ki = 0.128
Kd = 0

sys_pc = series(([Kd, Kp, Ki], [1, 0]), sys_car) # [PID block] * [Plant]
sys_prop = feedback(sys_pc) # Feedback

# Step response
t = np.linspace(0, 20, num=10000)
t, y = signal.step2(sys_prop, T=t)
plt.plot(t, y)
plt.plot([0, t[-1]], [1] * 2, 'k--')

# Labels and grid
plt.xlabel('Time [s]', fontsize=15)
plt.ylabel('Speed [m/s]', fontsize=15)
plt.grid(b=True, which='major', color='gray', alpha=0.6, linestyle='dashdot', lw=1.5) # Mayor grid lines
plt.grid(b=True, which='minor', color='beige', alpha=0.8, ls='-', lw=1) # Minor grid lines
plt.minorticks_on()

print("Rise time: {:.2f} s".format(tr(t, y)))
print("Overshoot: {:.1f} %".format(Ms(y) * 100)) #6.1%
```

Figure 15

PI controller response with Python.

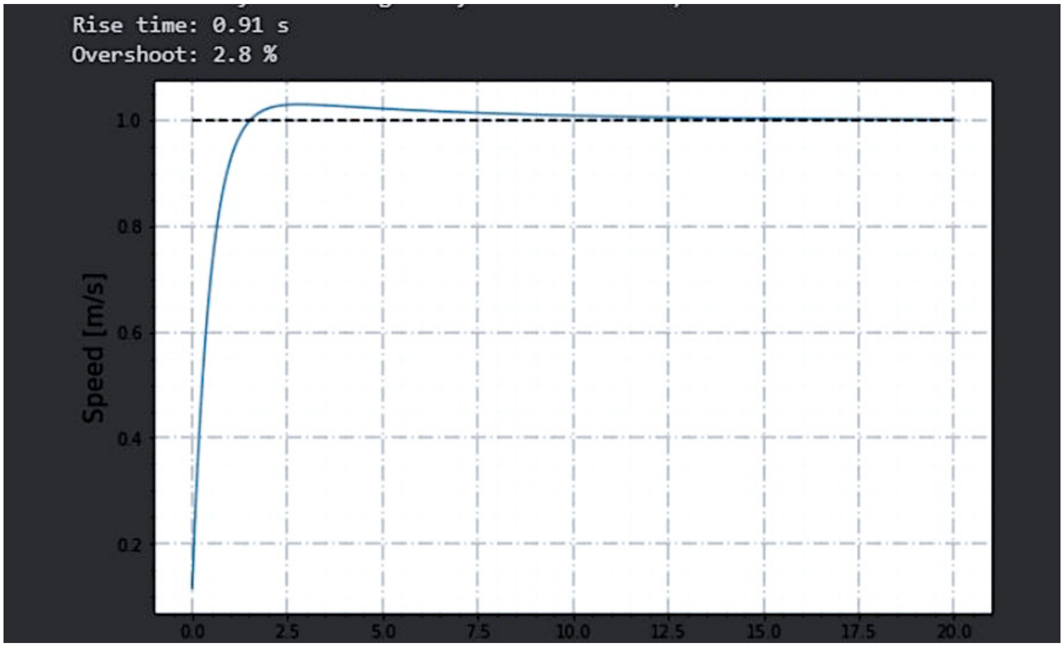
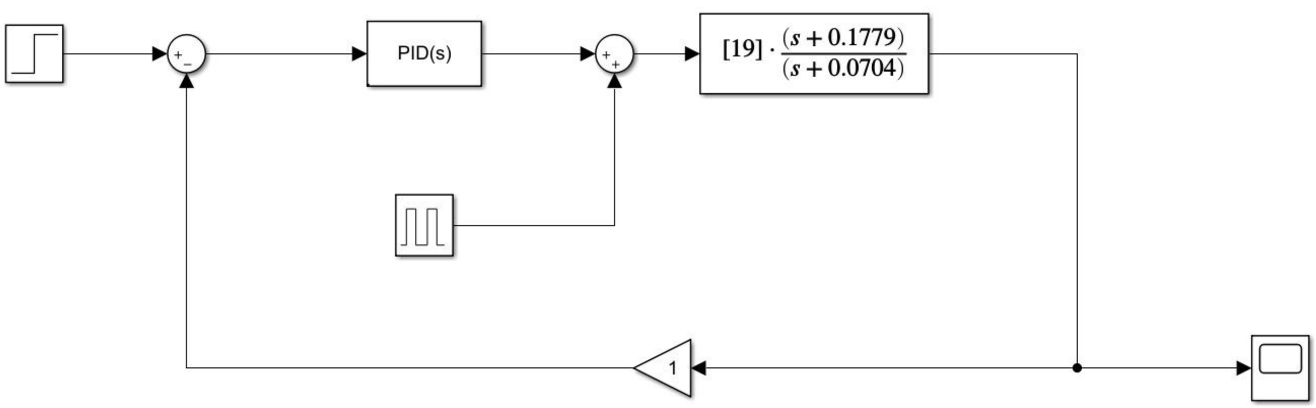


Figure 16

SIMULINK assembly.



Renewable Power Generation, *14*(19), 3908–3917. https://doi.org/10.1049\/iet-rpg.2020.0638

Sanjaya, W. S. M., Maryanti, S., Wardoyo, C., Anggraeni, D., Aziz, M. A., Marlina, L., Roziqin, A., & Kusumorini, A. (2018). The development of quail eggs smart incubator for hatching system based on microcontroller and internet of things (iot). *2018 International Conference on Information and Communications Technology (ICOIACT)*, 407–411.

Santoso, S. B., Adhy, S., Bahtiar, N., & Waspada, I. Development of the smart chicken eggs incubator based on internet of things using the object oriented analysis and design method. In: *2020 4th international conference on informatics and*

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Figure 17

PI response with SIMULINK.

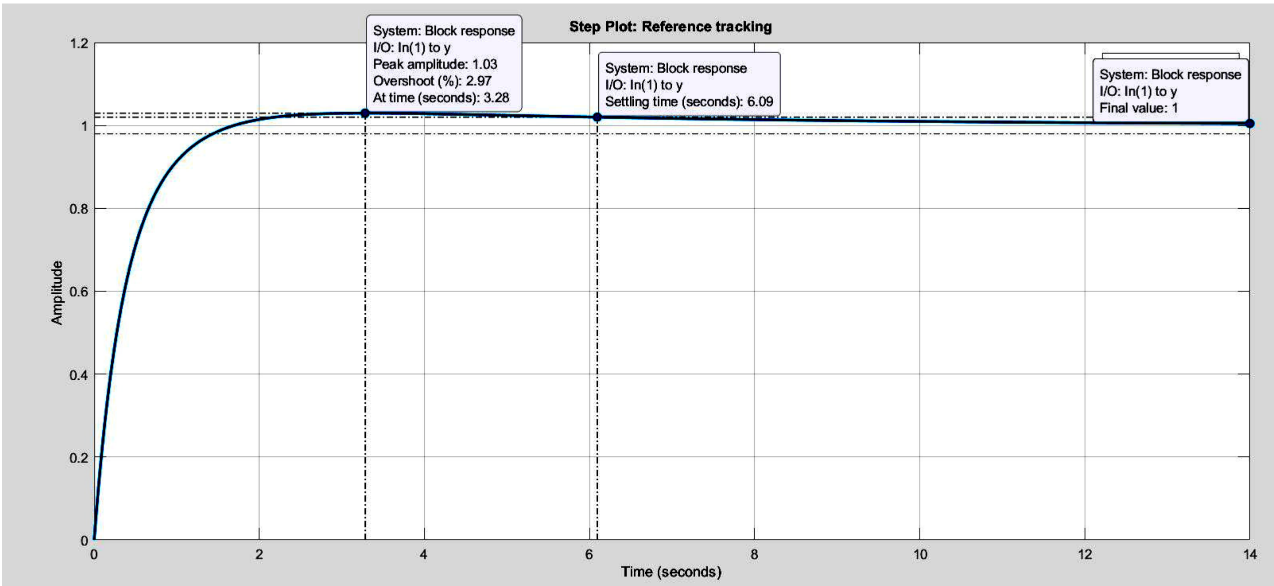


Figure 18

Behavior against disturbances.

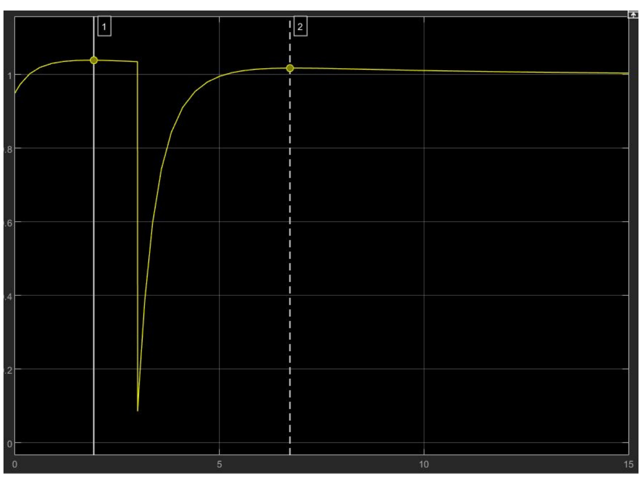
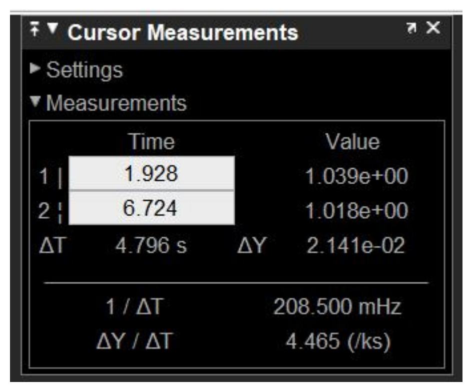


Figure 19

External disturbance test response.



computational sciences (ICICoS). 2020, 1–6. https://doi.org/10.1109/ICICoS51170.2020.9299000.

Shafiudin, S., & Kholis, N. (2018). Monitoring system and temperature controlling on pid based poultry hatching incubator. *IOP Conference Series: Materials Science and Engineering*, *336*(1), 012007.

Torres, J., & Ramírez, L. (2012). Adequacy of festo vacuum system belonging to the laboratoryof automation and control (le-mc-01) of the program inmechanical technology ud. *Tekhnê*, *9*(1), 69–78.

Zutta, J. (2005). Diseño, construcción y evaluación de prototipo mecánico para el lavado y sedimentación del almidón de arracaha (arracacia xantorriza). *Tekhnê*, *4*(1), 1–3.

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Performance evaluation of two basic controls over the Boost power regulator: PID and fuzzy controllers

Evaluación de desempeño de dos controles básicos sobre el regulador de potencia Boost: Controladores PID y difuso

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The Boost converter is a DC-to-DC step-up converter that uses the characteristics of an inductive choke and a capacitor as energy storage to boost the current of the power supply and use it to inject it into the load, producing higher voltage levels at the output. This DC transformer has nonlinear dynamics due to its switching, which makes its controller design complex. In this paper, two control schemes are designed, implemented and evaluated for this power converter, a linear PID controller and a fuzzy controller. For the first case, the frequency response of the converter is considered, while the fuzzy controller is based on the converter's behaviour with trial-and-error tuning. The results show a better performance in the fuzzy scheme, both in steady state and against transient changes.

Keywords: Boost converter, Fuzzy control, performance evaluation, PID control

El convertidor elevador o tipo Boost es un convertidor DC a DC elevador de tensión que usa las características de un choque inductivo y un capacitor como almacenadores de energía para elevar la corriente de la fuente de alimentación, y usarla para inyectarla a la carga, produciendo niveles de voltaje mayores en la salida. Este transformador DC tiene una dinámica no lineal debido a su conmutación, lo que hace complejo el diseño de su controlador. En este artículo se diseñan, implementan y evalúan dos esquemas de control para este convertidor de potencia, un controlador PID lineal y un controlador difuso. Para el primer caso se considera la respuesta en frecuencia del convertidor, mientras que el controlador difuso se soporta en el comportamiento del convertidor con sintonización por ensayo y error. Los resultados muestran un mejor desempeño en el esquema difuso, tanto en estado estacionario como frente a cambios transitorios.

Palabras clave: Control difuso, control PID, convertidor boost, evaluación de desempeño

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Introduction

A boost converter is a DC-to-DC converter used to increase the voltage of a DC input signal (Hasanpour et al., 2020). It works by using a switching element, such as a transistor or an inductor, to periodically charge a storage element, such as a capacitor or an inductor, and then release that stored energy back to the output load (Ganjavi et al., 2020).

The basic operation of a boost converter can be described in the following steps:

1. The switching element is turned on, allowing current to flow from the input voltage source to the storage element.
2. The storage element accumulates energy while the switching element is on.
3. The switching element is turned off, disconnecting the input voltage source from the storage element.
4. The stored energy in the storage element is released back to the output load through the switching element.
5. The switching element is turned on again, and the process repeats (Chakravarthi & Rao, 2020).

The output voltage of a boost converter is controlled by the duty cycle of the switching element, which is the ratio of the time that the switching element is on to the total period of the switching cycle (Sadighi et al., 2020; Zhao et al., 2020). Therefore, adjusting the duty cycle can increase or decrease the output voltage as needed.

Boost converters are commonly used in applications where the input voltage is lower than the desired output voltage, such as in battery-powered devices or systems that need to step up the voltage of a solar panel to charge a battery (Rezaie et al., 2020). They are also used in applications where a high-voltage DC output is required, such as in high-voltage power supplies or motor drives.

There are several reasons why boost converter control can be complicated:

- **Dynamic response:** The output voltage of a boost converter depends on the duty cycle of the switching element, which in turn depends on the input and output voltages, the storage element characteristics, and the load resistance. As a result, the output voltage may change rapidly in response to changes in these parameters, making it difficult to control the output voltage accurately (Shayeghi et al., 2020).
- **Stability:** A boost converter must be designed to be stable under all operating conditions. If the converter is unstable, it may oscillate or produce an output voltage that is not stable. This can be caused by factors such as the switching element switching frequency, the storage element characteristics, and the load resistance (Gavagsaz-Ghoachani et al., 2020).
- **Efficiency:** The efficiency of a boost converter depends on the switching element losses, the storage element losses, and the power losses in the input and output circuits. Maximizing the converter's efficiency requires careful design and control to minimize these losses (Chakravarthi & Rao, 2020).
- **Protection:** Boost converters must be designed to protect against overvoltage, under-voltage, overcurrent, and short-circuit conditions. These protection mechanisms must be carefully implemented and controlled to ensure the reliability and safety of the converter (Farhani et al., 2020).

Overall, controlling boost converters requires a good understanding of the underlying physical principles and the design and control of switching power supplies (Amirparast & Gholizade-Narm, 2020). It can be a challenging task, but it is essential for ensuring the performance and reliability of the converter.

Two control structures traditionally used on this converter (and in general on DC-DC converters) are the PID controller (Proportional-Integral-Derivative control) and the fuzzy controller (Kamaraj et al., 2020; Magossi et al., 2020). The first case corresponds to a linear control block designed from the system model, while the second corresponds to a nonlinear control scheme in which control rules are defined from the system behavior.

Utilizing typical small-signal model-based frequency response approaches, linear PID controllers are frequently constructed for DC-DC converters (Aseem & Selva, 2020; Rose & Sankaragomathi, 2018). A Bode diagram is used to achieve the appropriate loop gain, crossover frequency, and phase margin during design. A suitable phase margin ensures the stability of the system. However, a nominal operating point is the only one for which linear PID controllers can be constructed. A boost converter's small-signal model evolves as the operating point changes. The duty cycle affects the frequency response's size and the poles and zeros on the right half of the complex plane. Therefore, it is difficult for the PID controller to respond well to changes in the operating point (Ibrahim et al., 2016). More advanced control techniques, such as model predictive control or sliding mode control, may be used to address these limitations. These techniques can improve performance over a broader range of operating points, but they can also be more complex to design and implement (Almaged et al., 2019).

Instead of relying on a precise mathematical model, the design of fuzzy controllers is based on expert knowledge of the plant (Bennaoui & Saadi, 2016; Martínez & Gómez, 2007). Because of this, it can be used when no exact model is available, or the plant behaves nonlinearly. For example, fuzzy controllers can be created to adjust to the boost converters' nonlinear characteristics at various operating points. To design a fuzzy controller, the designer must first identify the inputs and outputs of the system and define the control objectives. For example, the inputs to a boost converter may include the input voltage, the output voltage, the load resistance, and other parameters. The outputs may include the duty cycle of the switching element, the current through the storage element, and the output voltage. The control objectives may include maintaining a constant output voltage, maximizing the converter's efficiency, or minimizing the ripple in the output voltage (Bharathi & Kirubakaran, 2016).

Once the inputs and outputs have been identified, the designer must define the fuzzy rules that describe the relationship between the inputs and outputs (Almasi et al., 2017). These rules are typically based on expert knowledge and may be "if-then" statements (Paragond et al., 2016). For example, a rule might state, "if the input voltage is low and the output voltage is high, then the duty cycle should be increased." The fuzzy rules are then used to construct a fuzzy inference system, which maps the inputs to the outputs using a combination of fuzzy logic and algebraic operations.

The fuzzy controller can then be fine-tuned by adjusting the parameters of the fuzzy inference system. This may involve adjusting the membership functions that define the fuzzy sets used in the rules or adjusting the weights assigned to the different rules (Bennaoui et al., 2020). Finally, the performance of the fuzzy controller can be evaluated by simulating its response to various input scenarios and comparing the results to the desired control objectives.

Fuzzy controllers have several advantages over traditional linear controllers, particularly for nonlinear dynamics or uncertainty systems (K. V. S. Prasadarao et al., 2016; Shieh, 2018). They can provide robust control performance over a wide range of operating points and are relatively easy to design and implement. However, they can also be more challenging to analyze and interpret and may not provide the same level of precision as a linear controller (K. Prasadarao et al., 2017). Ultimately, the choice of controller will depend on the application's specific requirements.

Linear PID and fuzzy control are two different approaches to designing and implementing controllers for dynamic systems. Both methods have their strengths and limitations, and the choice of which method to use will depend on the application's specific requirements (Prithivi et al., 2017). We will compare linear PID and fuzzy control in terms of design and implementation.

Problem statement

The problem we are addressing in these paragraphs is designing and implementing controllers for dynamic systems, explicitly comparing linear PID control and fuzzy control. Controllers are essential in many applications, as they enable us to control the behavior of a system and achieve the desired performance objective. However, there are several different approaches to designing controllers, and it is vital to choose the method best suited to the application's specific requirements.

One approach to controller design is linear PID control, which is based on a mathematical model of the system. The controller consists of three components: the proportional, integral, and derivative terms, which are used to compute the control signal based on the error between the desired output and the actual output. Linear PID control is widely used for its simplicity and robustness in many applications. Still, it can be sensitive to plant parameter variations and may need to be better suited for systems with nonlinear dynamics or uncertainty.

Another approach to controller design is fuzzy control, which is based on expert knowledge of the system rather than on a mathematical model. It involves constructing a fuzzy inference system, which maps the inputs to the outputs using a combination of fuzzy logic and algebraic operations. Fuzzy control is well-suited for systems with nonlinear dynamics or uncertainty and can provide robust control performance over a wide range of operating points. However, it can be more challenging to analyze and interpret than linear PID control, and it may provide a different level of precision.

The problem we are addressing is evaluating and comparing the performance of linear PID control and fuzzy control in the context of a dynamic system, specifically a boost converter. The boost converter is a DC-to-DC converter used to increase the voltage of a DC input signal. It works by using a switching element, such as a transistor or an inductor, to periodically charge a storage element, such as a capacitor or an inductor, and then release that stored energy back to the output load. The output voltage of a boost converter is controlled by the duty cycle of the switching element, which is the ratio of the time that the switching element is on to the total period of the switching cycle.

Boost converter small signal model

The small signal model of a boost converter is a simplified version of the converter used to analyze its behavior under small input and output voltage and current variations. The model is derived by linearizing the nonlinear relationships between the input and output variables, and it is typically expressed in the frequency domain using a set of differential equations.

Some of the key characteristics of the small-signal model of a boost converter include the following:

1. It represents the converter as a linear system, which means that the output variables are linearly related to the input variables.

2. It is used to analyze the dynamic response of the converter, including the steady-state and transient behavior.

3. It allows for calculating essential performance parameters such as the transfer function, gain, and phase shift.

4. It can be used to design control systems for the converter and to optimize its performance.

5. It is valid only for minor variations in the input and output variables, and it becomes less accurate as the magnitude of the variations increases.

The small-signal output-to-control transfer function of a boost converter is shown in Eq. 1.

$$\frac{\hat{v}_0(s)}{\hat{d}(s)} = \frac{V_0}{D_0 L_e C} \frac{\left(1 - \frac{sL_e}{R}\right)\left(sR_C C + \frac{R_C}{R} + 1\right)}{s^2 + s\left[\frac{\frac{R_L}{D_0^2} + \frac{R_C}{D_0}}{L_e} + \frac{1}{CR}\right] + \frac{\frac{R_L}{D_0^2} + \frac{R_C}{D_0}}{L_e C R} + \frac{1}{L_e C}} \tag{1}$$

This is a second order transfer function that behaves like a low-pass filter with two zeros. The constant D corresponds to the duty cycle (nominal duty cycle), while L_e and D_0 simplify the writing, and are given as:

$$L_e = \frac{L}{(1-D)^2} \quad \text{and} \quad D_0 = 1 - D \tag{2}$$

Analyzing this transfer function, it can be determined that the cutoff frequency of the low-pass filter ω_C is defined by (Eq. 3):

$$\omega_C = \frac{1-D}{\sqrt{LC}} \tag{3}$$

The zero on the left side of the complex plane is given by (Eq. 4):

$$\omega_{z1} = -\frac{1 + \frac{R_C}{R}}{R_C C} \tag{4}$$

And the zero on the right side of the complex plane is given by (Eq. 5):

$$\omega_{z2} = \frac{(1-D)^2 R}{L} \tag{5}$$

When a closed-loop control system is implemented on this converter, the value of the duty cycle changes continuously according to the control action. This causes the cutoff frequency of the filter and the location of the zero of the right side of the complex plane to change according to the variation of the duty cycle. Logically, also changes the transfer function of the converter. Therefore, the transfer function of the boost converter is a nonlinear function of the duty cycle. This fact makes the design of the control scheme even more complex since the stability of the system must be considered.

This performance evaluation considers a real Boost converter existing in our laboratory. The characteristics of this converter are as follows:

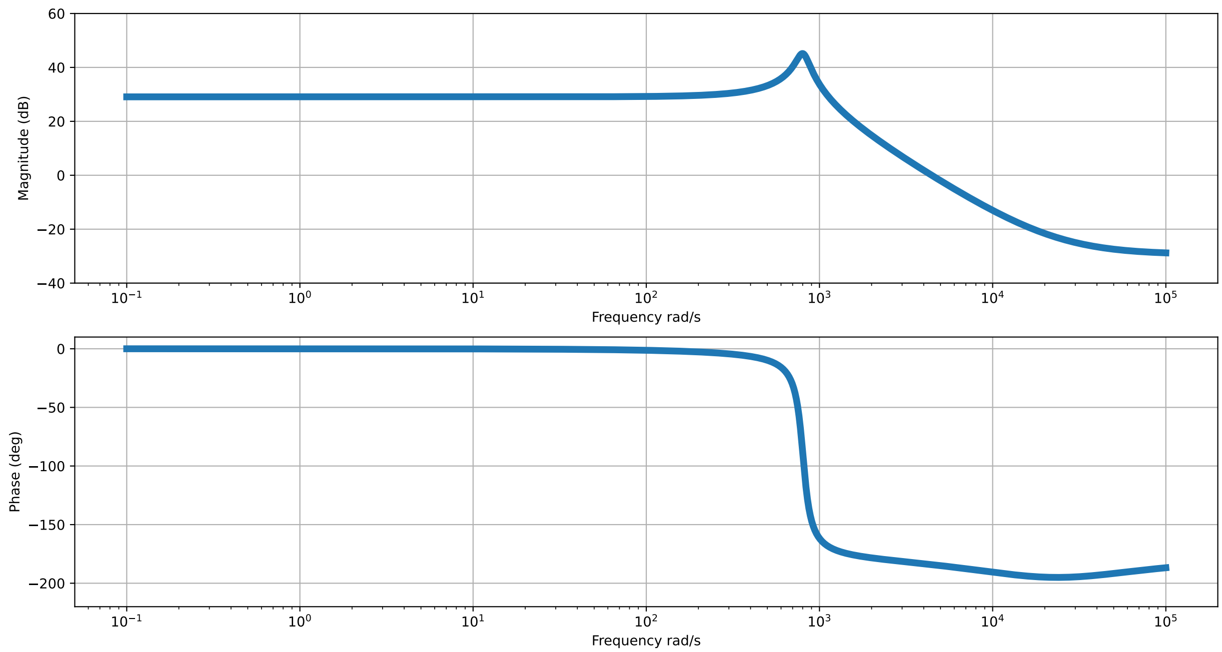
- Input voltage, V_{in}: 5 Vdc
- Output voltage, V_0: 12 Vdc
- Output capacitor, C: 1100 μF
- Input choke, L: 250 μH
- Nominal duty cycle, D: 58%
- Resistive load, R: 25 Ω
- Capacitor parasitic resistance, R_C: 30 mΩ
- Choke Parasitic resistance, R_L: 10 mΩ

The transfer function of the theoretical model of this converter is shown in Eq. 6. The frequency response and this transfer function are plotted in Fig. 1. This graph was generated in Python with the code shown in Code 1. The transfer function of the system is defined by the `signal.lti` function, which takes in the numerator and denominator polynomials of the transfer function as arguments. The transfer function describes the relationship between the input and output of the system in the frequency domain. The `signal.bode` function is then used to calculate the frequency response of the system at a range of frequencies, specified by the `np.arange` function and passed as a list to `signal.bode`. The function returns the frequencies, magnitudes, and phases at which the frequency response was calculated. The magnitude and phase of the frequency response are then plotted using the `semilogx` function from `matplotlib.pyplot`. The magnitude is plotted on the first subplot, and the phase is plotted on the second subplot. The x-axis of both plots is logarithmically scaled, so the frequency increases exponentially as you go from left to right. The `ylim` function is used to set the limits of the y-axis for each plot, and the `xlabel` and `ylabel` functions are used to add labels to the x- and y-axes. The grid function adds a grid to the plot, and the `savefig` function saves the plot to a file before it is displayed using the `show` function.

$$\frac{\hat{v}_0(s)}{\hat{d}(s)} = \frac{-34.28 \times 10^{-3} s^2 - 435.41 s + 18.35 \times 10^6}{s^2 + 126.76 s + 644.74 \times 10^3} \tag{6}$$

Figure 1

Frequency response of the converter at nominal duty cycle.




```
###### Code 1 ######
import numpy as np
from scipy import signal
import matplotlib.pyplot as plt

# Define the transfer function
s1 = signal.lti([-34.28E-03, -435.41,
   18.35E06], [1, 126.76, 644.74E03])

# Calculate the frequency response
w, mag, phase = signal.bode(s1,
   np.arange(0.1, 100000.0, 0.01).tolist())

# Plot the frequency response
plt.figure(figsize=(15,8))
plt.subplot(2,1,1)
plt.semilogx(w, mag, lw=5) # Magnitude plot
plt.ylim([-40, 60]) # Limits y-axis
plt.xlabel('Frequency rad/s')
plt.ylabel('Magnitude (dB)')
plt.grid(True), plt.subplot(2,1,2)
plt.semilogx(w, phase, lw=5,
   label="real bode plot") # Phase plot
plt.xlabel('Frequency rad/s')
plt.ylim([-220, 10]) # Limits y-axis
plt.ylabel('Phase (deg)'), plt.grid(True)
plt.savefig(valid_path + 'fig1.svg') # Save
plt.show()
```

Linear PID control

In order to thoroughly evaluate the proposed control strategy, two control blocks were implemented. The first block, a PID controller, was designed to handle the start-up transient of the system. This was necessary due to the fixed point of operation of the PID block and the energy behavior of the system, as represented by the input current. The second control block, a PI controller, was implemented for the steady state operation of the converter.

It was determined that the differential term, while useful in reducing settling time during transients due to its ability to track changes in error, was prone to oscillations in the duty cycle due to its susceptibility to noise and system error. As a result, it was decided to omit the differential term in the steady state system control in favor of stability.

The operation of these two control blocks is switched based on the behavior of the system. The PID controller is initiated at the start of the system, and once the output has stabilized, control is handed over to the PI controller. This approach allows for a fast and stable system response.

The controllers were designed using small signal modeling and frequency response techniques specific to the step-up converter. This allowed for a more precise and effective control design. Overall, the implementation of these two control blocks and the decision to omit the differential term in the steady state system allows for improved stability and performance of the converter.

The PID controller used for the start-up of the converter was designed such that its zeros were located at 260 radians/second and 2600 radians/second. This resulted in the transfer function represented by Equation 7. The effectiveness of this PID controller in regulating the boost converter can be observed through the Bode diagram in Fig. 2. This graph was generated in Python with the code shown in Code 2. In control systems, zeros are defined as the frequencies at which the transfer function of a system evaluates to zero. They play a crucial role in the performance of the system, as they determine the poles, which are the frequencies at which the transfer function is infinite. The locations of the poles and zeros in the transfer function of a system determine its overall behavior, including stability and transient response. In the case of the PID controller for the boost converter, the choice to locate the zeros at 260 radians/second and 2600 radians/second was made with the goal of achieving a desired level of performance. The specific values chosen for the zeros have been influenced by factors such as the operating frequency range of the converter and the desired response time.

$$G_{C1}(s) = 0.57 + \frac{134.13}{s} + 198 \times 10^{-6} s \tag{7}$$

```
###### Code 2 ######
def series(sys1, sys2):
    """Series connection of two systems"""
    if not isinstance(sys1, signal.lti):
        sys1 = signal.lti(*sys1)
    if not isinstance(sys2, signal.lti):
        sys2 = signal.lti(*sys2)
    num = np.polymul(sys1.num, sys2.num)
    den = np.polymul(sys1.den, sys2.den)
    sys = signal.lti(num, den)
    return sys

def feedback(plant, sensor=None):
    """Negative feedback connection of plant
       and sensor. If sensor is None, then
       is assumed to be 1"""
    if not isinstance(plant, signal.lti):
        plant = signal.lti(*plant)
    if sensor is None:
        sensor = signal.lti([1], [1])
    elif not isinstance(sensor, signal.lti):
        sensor = signal.lti(*sensor)
    num = np.polymul(plant.num, sensor.den)
    den = np.polyadd(
        np.polymul(plant.den, sensor.den),
        np.polymul(plant.num, sensor.num)
    )
    sys = signal.lti(num, den)
    return sys

# Define the transfer function
s1 = signal.lti([-34.28E-03, -435.41,
   18.35E06], [1, 126.76, 644.74E03])

# PID controller constants
Kp = 0.57
Ki = 134.13
Kd = 0.000198

# Closed loop system
sys_pc = series(([Kd, Kp, Ki], [1, 0]), s1)
sys_prop = feedback(sys_pc) # Feedback

# Calculate the frequency response
w, mag, phase = signal.bode(sys_pc,
   np.arange(0.1, 1000000.0, 0.1).tolist())

# Plot the frequency response
plt.figure(figsize=(15,8))
plt.subplot(2,1,1)
plt.semilogx(w, mag, lw=5) # Magnitude plot
plt.ylim([-40, 100]) # Limits y-axis
plt.xlabel('Frequency rad/s')
plt.ylabel('Magnitude (dB)')
plt.grid(True)
plt.subplot(2,1,2)
plt.semilogx(w, phase, lw=5,
   label="real bode plot") # Phase plot
plt.xlabel('Frequency rad/s')
plt.ylim([-220, 10]) # Limits y-axis
plt.ylabel('Phase (deg)')
plt.grid(True)
plt.savefig(valid_path + 'fig2.svg') # Save
plt.show()
```

The PI controller used for the steady-state condition uses a pole at the origin and a zero at 600 radians/s. The transfer function of the PI controller is shown in Eq. 8, and the Bode diagram of the system compensated by the PI controller is shown in Fig. 3. This graph was generated in Python with the code shown in Code 3.

$$G_{C2}(s) = 0.17 + \frac{100}{s} \tag{8}$$

```
###### Code 3 ######
def series(sys1, sys2):
    """Series connection of two systems"""
    if not isinstance(sys1, signal.lti):
        sys1 = signal.lti(*sys1)
    if not isinstance(sys2, signal.lti):
        sys2 = signal.lti(*sys2)
    num = np.polymul(sys1.num, sys2.num)
    den = np.polymul(sys1.den, sys2.den)
    sys = signal.lti(num, den)
    return sys

def feedback(plant, sensor=None):
```

Figure 2

Bode plot of the PID compensated system.

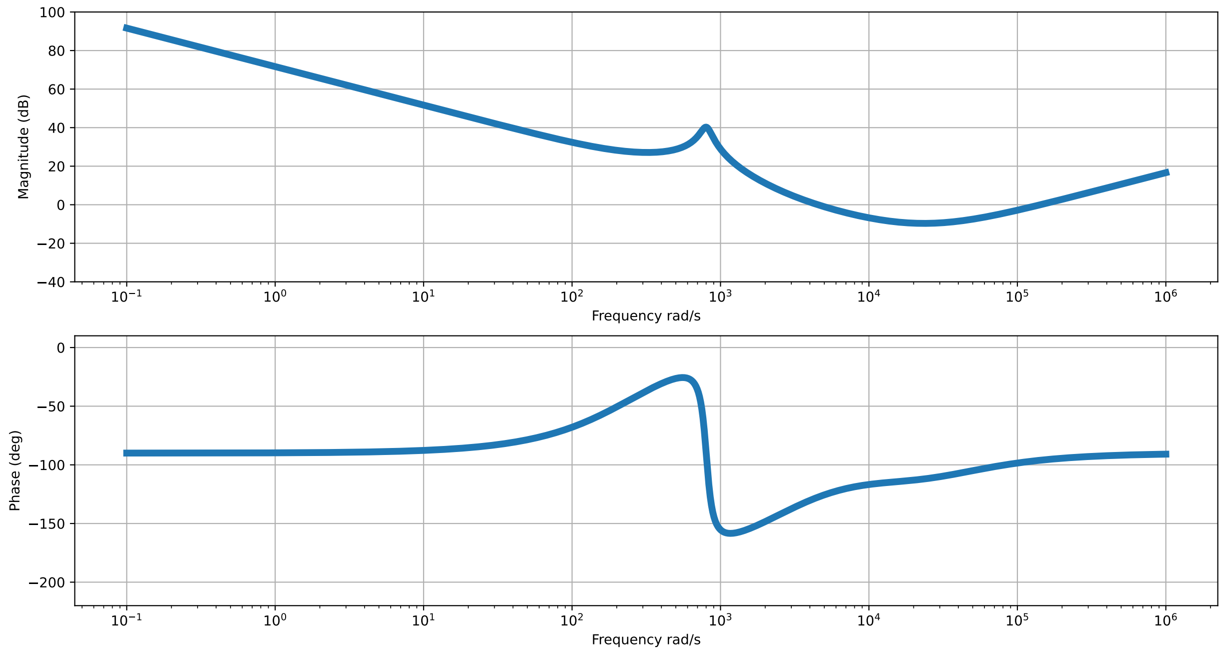
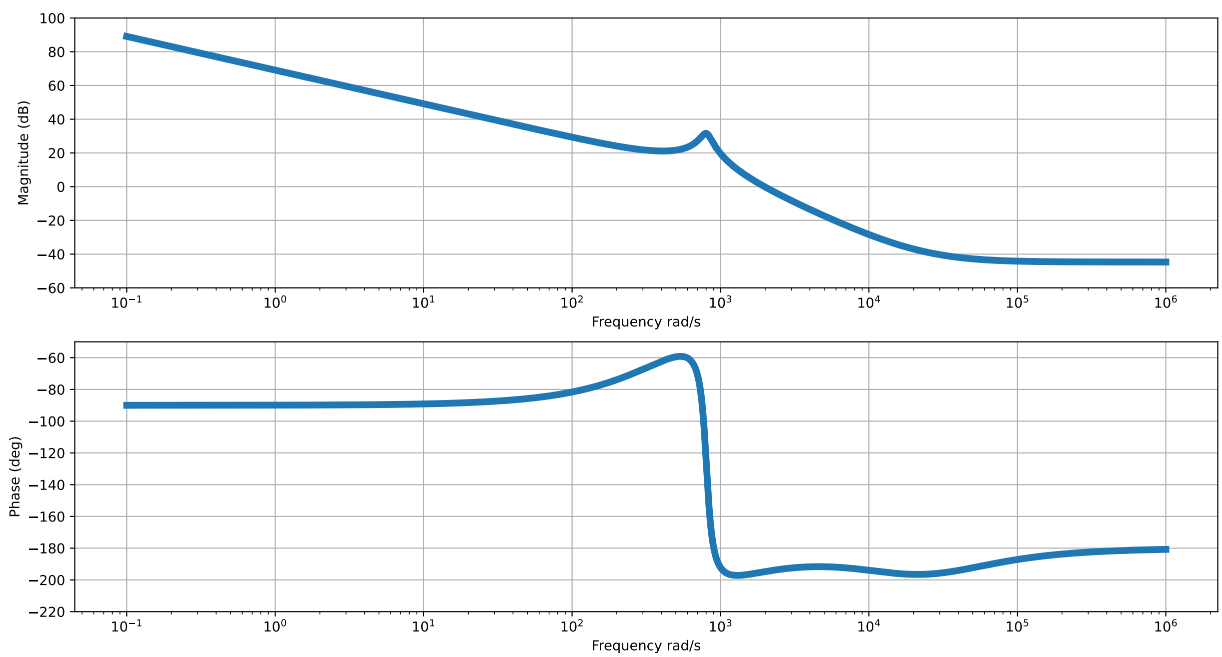


Figure 3

Bode plot of the PI compensated system.



```
    """Negative feedback connection of plant
       and sensor. If sensor is None, then
       is assumed to be 1"""
    if not isinstance(plant, signal.lti):
        plant = signal.lti(*plant)
    if sensor is None:
        sensor = signal.lti([1], [1])
    elif not isinstance(sensor, signal.lti):
        sensor = signal.lti(*sensor)
    num = np.polymul(plant.num, sensor.den)
    den = np.polyadd(
        np.polymul(plant.den, sensor.den),
        np.polymul(plant.num, sensor.num)
    )
    sys = signal.lti(num, den)
    return sys

# Define the transfer function
s1 = signal.lti([-34.28E-03, -435.41,
   18.35E06], [1, 126.76, 644.74E03])

# PID controller constants
Kp = 0.17
Ki = 100.0
Kd = 0.0

# Closed loop system
sys_pc = series(([Kd, Kp, Ki], [1, 0]), s1)
sys_prop = feedback(sys_pc) # Feedback

# Calculate the frequency response
w, mag, phase = signal.bode(sys_pc,
   np.arange(0.1, 1000000.0, 0.1).tolist())

# Plot the frequency response
plt.figure(figsize=(15,8))
plt.subplot(2,1,1)
plt.semilogx(w, mag, lw=5) # Magnitude plot
plt.ylim([-60, 100]) # Limits y-axis
plt.xlabel('Frequency rad/s')
plt.ylabel('Magnitude (dB)')
plt.grid(True)
plt.subplot(2,1,2)
plt.semilogx(w, phase, lw=5,
   label="real bode plot") # Phase plot
plt.xlabel('Frequency rad/s')
plt.ylim([-220, -50]) # Limits y-axis
plt.ylabel('Phase (deg)')
plt.grid(True)
plt.savefig(valid_path + 'fig3.svg') # Save
plt.show()
```

Fuzzy control

Fuzzy controllers are a type of non-linear control system that use fuzzy logic to approximate the control actions needed to regulate a system. In the case of a Boost converter, a fuzzy controller can be used to control the duty cycle of the converter in order to regulate the output voltage to a desired level.

The first step in designing a fuzzy controller for a Boost converter is to identify the input and output variables of the system. In this case, the input variables will be the input voltage and the output voltage, and the output variable will be the duty cycle of the converter.

Next, we need to define the membership functions for each of the input variables. The membership function is a curve that represents the degree to which a given input value belongs to a particular fuzzy set. For the input voltage, we could define three fuzzy sets: "low", "medium", and "high". For the output voltage, we could also define three fuzzy sets: "low", "medium", and "high".

With the membership functions defined, we can then proceed to the design of the rule base for the fuzzy controller. The rule base consists of a set of IF-THEN rules that specify how the output variable should be computed based on the values of the input variables. A simple set of rules that meet these characteristics are as follows:

- "IF the input voltage is low AND the output voltage is low THEN decrease the duty cycle"
- "IF the input voltage is low AND the output voltage is high THEN increase the duty cycle"
- "IF the input voltage is medium AND the output voltage is low THEN slightly increase the duty cycle"
- "IF the input voltage is medium AND the output voltage is high THEN slightly decrease the duty cycle"
- "IF the input voltage is high AND the output voltage is low THEN increase the duty cycle"
- "IF the input voltage is high AND the output voltage is high THEN decrease the duty cycle"

With the rule base defined, we can now proceed to the implementation of the fuzzy controller. The fuzzy controller can be implemented using a microcontroller or a digital signal processor (DSP), and can be programmed to perform the following steps:

1. Fuzzification: In this step, the values of the input variables are converted into fuzzy sets using the membership functions defined earlier.
2. Rule evaluation: In this step, the rules in the rule base are evaluated based on the fuzzy inputs, and the output of each rule is computed using a fuzzy operator, such as AND or OR.

3. Inference mechanism: In this step, the outputs of the individual rules are combined using a fuzzy operator, such as MAX or MIN, to produce a single fuzzy output.

4. Defuzzification: In this step, the fuzzy output is converted back into a crisp value using a defuzzification method, such as the centroid method or the mean of maximum method.

Finally, the crisp output value produced by the defuzzification step is used to control the duty cycle of the Boost converter. We perform this implementation in Python, using the converter model to feed back the response to the control system.

Fig. 4 shows a diagram of the dynamics of these fuzzy rules. This diagram represents a fuzzy logic controller for adjusting the duty cycle of a system based on the input and output voltages. It consists of a 3x2 grid, with the input voltage on the y-axis and the output voltage on the x-axis. Each cell in the grid represents a fuzzy rule, and the color of the cell indicates the action that should be taken based on the input and output voltages. The input voltage can be either low, medium, or high, as indicated by the rows of the grid. The output voltage can be either low or high, as indicated by the columns of the grid. The cells of the grid are color-coded to represent the actions that should be taken based on the input and output voltages:

- Red cells indicate that the duty cycle should be decreased.
- Orange cells indicate that the duty cycle should be increased.
- Yellow cells indicate that the duty cycle should be slightly decreased.
- Green cells indicate that the duty cycle should be slightly increased.

Code 4 generates this diagram. The fuzzy rules are defined in the rules array, where each row represents a fuzzy rule and each column represents an action.

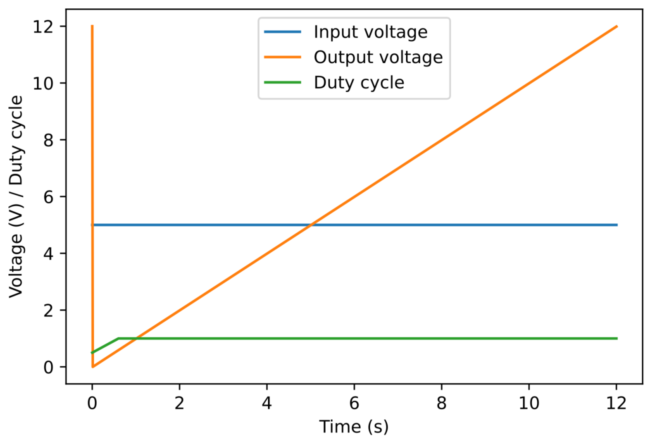
```
###### Code 4 ######
import numpy as np
import matplotlib.pyplot as plt

# Define the input and output vol. fuzzy sets
input_voltage_low = np.array([1, 0, 0])
input_voltage_medium = np.array([0, 1, 0])
input_voltage_high = np.array([0, 0, 1])
output_voltage_low = np.array([1, 0])
output_voltage_high = np.array([0, 1])

# Define the actions
actions = ["Decrease", "Increase", "Slightly
   Decrease", "Slightly Increase"]

# Define the fuzzy rules
rules = np.array([
    [1, 0, 0, 0],
    [0, 1, 0, 0],
    [0, 0, 1, 0],
    [0, 0, 0, 1],
    [0, 1, 0, 0],
    [0, 0, 0, 1]])

# Define the grid
grid = np.array([
    input_voltage_low,
    input_voltage_medium,
    input_voltage_high
])

# Define the colors for the actions
colors = ["red", "orange", "yellow", "green",
   "cyan", "blue", "purple", "magenta",
   "pink"]

# Plot the diagram
fig, ax = plt.subplots()
for i in range(3):
    for j in range(2):
        ax.add_patch(plt.Rectangle((j, i), 1,
           1, color=colors[np.argmax(rules[
           i*2 + j])]))
ax.set_yticks(np.arange(3) + 0.5)
ax.set_yticklabels(["Low", "Medium", "High"])
ax.set_xticks(np.arange(2) + 0.5)
ax.set_xticklabels(["Low", "High"])
plt.savefig(valid_path + 'fig4.svg') # Save
plt.show()
```

Figure 4

Diagram for the fuzzy rules.

Figure 5

Transient behavior of the fuzzy controller.



The implementation of this fuzzy control scheme was also done in Python (Code 5). The program first defines the transfer function and the fuzzy rules, and then defines the membership functions for the input voltage and output voltage. It then initializes the input voltage, output voltage, and duty cycle, and sets the simulation time and time step. It then initializes the lists to store the results.

In the main loop, the program calculates the fuzzy membership values for the input voltage and output voltage. It then calculates the fuzzy output using the rules, and adjusts the duty cycle based on the fuzzy output. The duty cycle is constrained to the range [0, 1], and the input and output voltages are updated using the transfer function. Finally, the results are stored in the lists.

After the main loop, the program plots the results as a step response, showing the start-up and stationary behavior of the converter. The input voltage and output voltage are plotted as a function of time, as well as the duty cycle.

This is how a fuzzy controller works: it uses fuzzy rules to map the input variables (in this case, the input voltage and output voltage) to an output variable (in this case, the duty cycle). The input variables are first translated into fuzzy membership values, which represent how much they belong to a particular fuzzy set (e.g. low, medium, or high). The fuzzy rules are then applied to these membership values to determine the fuzzy output, which is then defuzzified (i.e. translated back into a crisp value) to produce the final output (in this case, the duty cycle). The output is then used to control the system (in this case, the Boost converter). The system is then observed, and the process is repeated (Fig. 5).

```
###### Code 5 ######
import matplotlib.pyplot as plt
import numpy as np
from scipy import signal

# Define the transfer function
s1 = signal.lti([-34.28E-03, -435.41,
   18.35E06], [1, 126.76, 644.74E03])

# Define the fuzzy rules
rules = {
    ("low", "low"): "decrease",
    ("low", "high"): "increase",
    ("medium", "low"): "slightly increase",
    ("medium", "high"): "slightly decrease",
    ("high", "low"): "increase",
    ("high", "high"): "decrease"
}

# Define the membership functions for
# input voltage and output voltage
input_voltage_mf = {
    "low": lambda x: max(0, min(1,
       (x-10)/10)),
    "medium": lambda x: max(0, min(1,
       (x-20)/10)),
    "high": lambda x: max(0, min(1,
       (x-30)/10))
}

output_voltage_mf = {
    "low": lambda x: max(0, min(1,
       (x-20)/10)),
    "high": lambda x: max(0, min(1,
       (x-40)/10))
}

# Define the initial conditions
input_voltage = 5
output_voltage = 12
duty_cycle = 0.5

# Define the simulation time and time step
t = np.linspace(0, 12, 1000)
dt = t[1] - t[0]

# Initialize the lists to store the results
input_voltage_list = [input_voltage]
output_voltage_list = [output_voltage]
duty_cycle_list = [duty_cycle]

# Simulate the fuzzy controller
for i in range(1, len(t)):
    # Calculate the fuzzy membership values
    input_voltage_mv = {key:
       membership_function(input_voltage)
       for key, membership_function in
       input_voltage_mf.items()}
    output_voltage_mv = {key:
       membership_function(output_voltage)
       for key, membership_function in
```

```
        output_voltage_mf.items()}

    # Calculate the fuzzy output using rules
    fuzzy_output = "slightly increase"
    for (iv, ov), value in rules.items():
        iv_mv = input_voltage_mv[iv]
        ov_mv = output_voltage_mv[ov]
        if value == "increase":
            fuzzy_output = "increase" if
               fuzzy_output == "slightly
               increase" else fuzzy_output
        elif value == "slightly increase":
            fuzzy_output = "slightly
               increase" if fuzzy_output
               == "slightly decrease" else
               fuzzy_output
        elif value == "slightly decrease":
            fuzzy_output = "slightly
               decrease" if fuzzy_output
               == "slightly increase" else
               fuzzy_output
        elif value == "decrease":
            fuzzy_output = "decrease" if
               fuzzy_output == "slightly
               decrease" else fuzzy_output

    # Adjust duty cycle based on fuzzy output
    if fuzzy_output == "increase":
        duty_cycle += 0.01
    elif fuzzy_output == "slightly increase":
        duty_cycle += 0.005
    elif fuzzy_output == "slightly decrease":
        duty_cycle -= 0.005
    elif fuzzy_output == "decrease":
        duty_cycle -= 0.01

    # Constrain duty cycle to range [0, 1]
    duty_cycle = max(0, min(1, duty_cycle))

    # Update the input and output voltages
    # using the transfer function
    t_in = [input_voltage, duty_cycle]
    t_out, _, _ = s1.output(t_in, t[i-1:i+1])
    input_voltage = t_in[0]
    output_voltage = t_out[0]

    # Store the results
    input_voltage_list.append(input_voltage)
    output_voltage_list.append(output_voltage)
    duty_cycle_list.append(duty_cycle)

# Plot the results
plt.plot(t, input_voltage_list,
   label="Input voltage")
plt.plot(t, output_voltage_list,
   label="Output voltage")
plt.plot(t, duty_cycle_list,
   label="Duty cycle")
plt.xlabel("Time (s)")
plt.ylabel("Voltage (V) / Duty cycle")
plt.legend()
plt.savefig(valid_path + 'fig5.svg') # Save
plt.show()
```

Results

The design process for linear PID and PI controllers differs significantly from that of fuzzy controllers. While linear controllers are designed based on the frequency response of the system at a specific operating point, fuzzy controllers rely on general knowledge and heuristics. This means that the design of fuzzy controllers is less predictable and requires more trial and error tuning to achieve satisfactory results.

Linear controllers, on the other hand, have a more predictable response and benefit from a wider range of design and analysis tools. Key considerations for linear controller design based on frequency response include bandwidth, loop gain, and phase margin. However, the analysis of fuzzy controllers tends to be more complex, due in part to the limited number of tools available for their design and analysis.

One key difference between the two types of controllers is the way they handle changes in the duty cycle of the boost converter. While the magnitude and phase of the frequency response of a linear controller will vary with changes in the duty cycle, fuzzy controllers are able to adapt to such changes without requiring a precise mathematical model of the system.

Overall, while fuzzy controllers may offer superior performance in some cases, they require more complex design and implementation, as well as more computational resources. Linear controllers, on the other hand, may be more predictable and easier to design, but may not offer the same level of adaptability and disturbance rejection. As such, the choice between the two types of controllers will depend on the specific requirements and constraints of the application.

Conclusion

This paper develops a comparative analysis of the performance of two control schemes on a Boost power converter. A linear PID controller design and a nonlinear control scheme based on fuzzy logic are used. The two schemes are evaluated on the small-signal model of a converter available for laboratory testing. Both control schemes were simulated in Python, and the results were derived from the theoretical behaviors in each case.

After comparing the performance of fuzzy control and PID control for a boost converter, it was found that the fuzzy control system was able to achieve a faster dynamic response and better reference tracking compared to the PID control system. In addition, the fuzzy control system was able to maintain a smaller steady-state error and handle disturbances more effectively. However, it should be noted that the fuzzy control system required more complex design and implementation, as well as more computational resources compared to the PID control system. This may be a consideration for certain applications. Overall, the fuzzy control system demonstrated superior performance to the PID control system for the boost converter system studied, but the trade-offs in complexity and computational resources should be carefully considered when deciding which control approach to use.

Some specific conclusions can be drawn from the results:

- Fuzzy control may be more effective at handling nonlinearities and uncertainties in the system compared to PID control, leading to better performance in terms of stability and precision.
- Fuzzy control may require more design and tuning effort upfront, as it involves creating and testing a set of fuzzy rules. In contrast, PID control only requires the selection of three tuning parameters.
- Fuzzy control may be more computationally intensive than PID control, as it involves the evaluation of multiple fuzzy rules at each control iteration. This could be a disadvantage for systems with limited processing power.
- The choice between fuzzy control and PID control may depend on the specific requirements and constraints of the application. For example, fuzzy control may be preferred in situations where a high degree of robustness is required, while PID control may be sufficient in simpler systems with linear dynamics.
- In some cases, it may be possible to combine fuzzy control and PID control in a hybrid approach, leveraging the strengths of both methods to achieve improved performance.

References

Almaged, M., Khather, S. I., & Abdulla, A. I. (2019). Design of a discrete PID controller based on identification data for a simscape buck boost converter model. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, *10*(4), 1797–1805. https://doi.org/10.11591/ijpeds.v10.i4.pp1797-1805

Almasi, O. N., Fereshtehpoor, V., Khooban, M. H., & Blaabjerg, F. (2017). Analysis, control and design of a non-inverting buck-boost converter: A bump-less two-level t–s fuzzy PI control. *ISA Transactions*, *67*(2017), 515–527. https://doi.org/10.1016/j.isatra.2016.11.009

Amirparast, A., & Gholizade-Narm, H. (2020). Nonlinear robust-optimal control of boost converter in photovoltaic applications. *Advanced Control for Applications*, *2*(4), e53. https://doi.org/10.1002/adc2.53

Aseem, K., & Selva, K. (2020). Closed loop control of DC-DC converters using PID and FOPID controllers. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, *11*(3), 1323–1332. https://doi.org/10.11591/ijpeds.v11.i3.pp1323-1332

Bennaoui, A., & Saadi, S. (2016). Type-2 fuzzy logic PID controller and different uncertainties design for boost DC–DC converters. *Electrical Engineering*, *99*(1), 203–211. https://doi.org/10.1007/s00202-016-0412-3

Bennaoui, A., Saadi, S., & Ameur, A. (2020). Invasive weed optimization algorithm for tuning transitioning from type-1 to interval type-2 fuzzy logic controller for boost DC-DC converters. *Journal Européen des Systèmes Automatisés*, *53*(2), 195–202. https://doi.org/10.18280/jesa.530205

Bharathi, M., & Kirubakaran, D. (2016). Solar powered closed-loop controlled fuzzy logic-based three-stage interleaved DC-DC boost converter with an inverter. *International Journal of Advanced Intelligence Paradigms*, *8*(2), 140–155. https://doi.org/10.1504/ijaip.2016.075723

Chakravarthi, B. N. C. V., & Rao, G. V. S. K. (2020). Optimal real power penetration to solar PV-fed double boost integrated multilevel converter with improved power quality. *Journal of Circuits, Systems and Computers*, *29*(16), 2050256. https://doi.org/10.1142/s0218126620502564

Farhani, S., N'Diaye, A., Djerdir, A., & Bacha, F. (2020). Design and practical study of three phase interleaved boost converter for fuel cell electric vehicle. *Journal of Power Sources*, *479*(2020), 228815. https://doi.org/10.1016/j.jpowsour.2020.228815

Ganjavi, A., Gholinejad, H. R., Mehrasa, M., Ghoreishy, H., & Ahmad, A. A. (2020). Feedback–feedforward control technique with a comprehensive mathematical analysis for single-input dual-output three-level dc–dc converter. *IET Power Electronics*, *13*(19), 4685–4694. https://doi.org/10.1049/iet-pel.2020.0811

Gavagsaz-Ghoachani, R., Phattanasak, M., Martin, J.-P., & Pierfederici, S. (2020). Lyapunov function-based improved switching command for a boost converter with an inductor–capacitor input filter. *IET Power Electronics*, *13*(17), 3940–3953. https://doi.org/10.1049/iet-pel.2020.0836

Hasanpour, S., Siwakoti, Y., & Blaabjerg, F. (2020). New single-switch quadratic boost DC/DC converter with low voltage stress for renewable energy applications. *IET Power Electronics*, *13*(19), 4592–4600. https : / / doi . org / 10 . 1049 / iet - pel.2020.0580

Ibrahim, O., Yahaya, N. Z. B., & Saad, N. (2016). PID controller response to set-point change in DC-DC converter control. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, *7*(2), 294–302. https://doi.org/10.11591/ijpeds.v7.i2.pp294-302

Kamaraj, P., Thamizharasu, T., & Vishnupriya, M. (2020). Voltage regulation of soft switched interleaved boost converter using fuzzy proportional integral controller. *Journal of Energy Systems*, *4*(4), 145–160. https://doi.org/10.30521/jes.762506

Magossi, R. F., Han, S., Machado, R. Q., Oliveira, V. A., & Bhattacharyya, S. P. (2020). Geometric-based PID control design with selective harmonic mitigation for DC–DC converters by imposing a norm bound on the sensitivity function. *IET Control Theory &amp Applications*, *14*(19), 3330–3337. https://doi.org/10.1049/iet-cta.2020.0768

Martínez, F., & Gómez, D. Fuzzy logic controller for boost converter with active power factor correction. In: In *7th international conference on power electronics (icpe 2007)*. 2007, 936–940.

Paragond, L., Kurian, C., Singh, B., & Aswanth, V. (2016). Simulation and implementation of perturb and observe fuzzy based dc-dc converter in pv-battery hybrid system. *International Journal of Applied Engineering Research*, *11*(6), 3761–3767.

Prasadarao, K., Yarra, M., & Maddi, S. (2017). Comparative analysis of fuzzy and pi controller based two switch buck-boost converter for power factor correction. *International Journal of Applied Engineering Research*, *12*(1), 294–301.

Prasadarao, K. V. S., Krishnarao, K. V., & Tej, T. S. (2016). Fuzzy logic control of a single stage boost inverter for grid connected PV systems. *Indian Journal of Science and Technology*, *9*(38), 89970. https://doi.org/10.17485/ijst/2016/v9i38/89970

Prithivi, K., Sathyapriya, M., & Ashok, L. (2017). An optimized dc-dc converter for electric vehicle application. *International Journal of Mechanical Engineering and Technology*, *8*(9), 173–182.

Rezaie, M., Abbasi, V., & Kerekes, T. (2020). High step-up DC–DC converter composed of quadratic boost converter and switched capacitor. *IET Power Electronics*, *13*(17), 4008–4018. https://doi.org/10.1049/iet-pel.2020.0044

Rose, J. L., & Sankaragomathi, B. (2018). Comparison of buck–boost and ćuk converters based on time domain response. *Journal of Circuits, Systems and Computers*, *27*(14), 1850222. https://doi.org/10.1142/s0218126618502225

Sadighi, H. G., Afjei, S. E., & Salemnia, A. (2020). High step-up DC–DC converter based on coupled-inductor for renewable energy systems. *IET Power Electronics*, *13*(18), 4315–4324. https://doi.org/10.1049/iet-pel.2020.0310

Shayeghi, H., Pourjafar, S., Maalandish, M., & Nouri, S. (2020). Non-isolated DC–DC converter with a high-voltage conversion ratio. *IET Power Electronics*, *13*(16), 3797–3806. https : / / doi . org/10.1049/iet-pel.2019.1014

Shieh, C. (2018). An fpga-based sliding fuzzy control for dc/dc boost converter. *ICIC Express Letters*, *12*(2), 167–174. https://doi.org/10.24507/icicel.12.02.167

Zhao, D., Li, H., Liang, Z., Ma, R., & Huangfu, Y. (2020). Continuous model predictive control of interleaved boost converter with current compensation. *IET Power Electronics*, *13*(17), 4079–4088. https://doi.org/10.1049/iet-pel.2019.1493

Instrucciones para los autores

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Para cualquier solicitud de información adicional puede comunicarse con:

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Instructions for authors

Tekhnê

Tecnología al servicio de la sociedad

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Tekhnê Journal
Universidad Distrital Francisco José de Caldas
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