PhD Thesis
Soft-Landing Control of Short-Stroke Reluctance Actuators
Contributions and Publications

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Contributions

Most contributions are the result of research work carried out in the Department of Computer Science and Systems Engineering, in the School of Engineering and Architecture of the University of Zaragoza; and in the BSH Competence Center for Induction Development in Zaragoza, Spain. Additional contributions originated from a three-month research stay that was conducted at the Department of Electrical Engineering of the Eindhoven University of Technology, in the Netherlands.

For clarity, the main contributions are divided into categories corresponding to different chapters of the thesis:

2 System modeling. Two model types have been proposed. On the one hand, the basic model was proposed for the first time and presented at the 56th IEEE Conference on Decision and Control [6]. The main contribution regarding this model is the system representation with a hybrid automaton which accounts for the discrete behavior of the mechanical dynamics. On the other hand, the complete model was proposed in a paper which has been accepted for its publication in Mechatronics [4]. The main contributions of the second proposal are the gap reluctance function and, most notably, the dynamical equation of the magnetomotive force in the core, which characterizes magnetic hysteresis and saturation phenomena. Another idea is the model reduction, which transforms the electromagnetic subsystem and ensures that their parameters are identifiable from measurements of electrical signals.

3 Optimal control design. On the one hand, our main optimal control proposal is published in the IEEE Transactions on Control Systems Technology [2]. The primary contribution is the addition of probability functions in the problem formulation. Specifically, uncertainty in the contact position is included and the soft-landing optimal control is formulated in order to minimize the expectations of the contact velocity and acceleration. Furthermore, the advantages of utilizing the electrical current as the control input for reluctance actuators are discussed and, in consequence, the optimization of the current signal is included in the formulation of the problem. On the other hand, we have also collaborated on the design of open-loop control signals solving deterministic optimal control problems. The contribution is the analysis of the open-loop control strategies on perturbed systems via a Monte Carlo method. It has been presented the 17th European Control Conference [8].

4 **Run-to-run control**. The first main contribution of the R2R proposal is the search algorithm, based on Bayesian optimization. In the preliminary proposal, presented at the 17th European Control Conference [7], several adjustments are introduced to the algorithm: the limitation of the number of stored data by means of the combination or removal of observations, and the definition of a new acquisition function. For the final proposal, published in the IEEE/ASME Transactions on Mechatronics [3], new ideas are introduced regarding the search function, e.g. adaptive search bounds and an improved acquisition function. Moreover, as the second main contribution, the input signals are parameterized based on a feedforward controller, which relates the decision variables to parameters of the dynamical model. It exploits the flatness property of the dynamical model to derive a simple algebraic expression to calculate the input signal from the model parameters.

5 **Feedback control**. A robust SMC controller has been developed for reluctance actuators, and presented at the 21st IFAC World Congress [9]. The first contribution is the design of the controller as a switching model-free SMC, which works for every dynamic mode of the system. The second contribution is the analysis of the influence of the sampling rate on the impact velocities.

6 **State estimation**. The final contribution of the aforementioned paper presented at 56th IEEE Conference on Decision and Control [6] is a stochastic state observer based on a discretized version of the proposed basic model and the unscented Kalman filter. Two patent applications have been submitted in relation to its application for electromechanical relays [10] and solenoid valves [11] in cooking appliances. Moreover, the stochastic observer has served as the foundation for the main estimation proposal. It is described in a manuscript, which is under review at the time of writing [5]. It introduces two ideas that have not been previously explored for this class of actuators. Firstly, the state estimation is approached as a smoothing problem of a stochastic process, in which the state at a given time is refined by using future observation samples. Regarding the second main contribution, the estimator is designed using a novel set of observable variables. In addition to the electrical signals, commonly considered as the input and output of the system, the proposed estimator directly exploits discrete information related to its state, in particular whether the mover is resting at one of the contacts or moving. In the context of state estimation, we have also collaborated on the development of two novel techniques to estimate in real time the magnetic flux and other electromagnetic variables of reluctance actuators. They have been published in the IEEE Transactions on Industrial Electronics [1].

Journal articles

[1] E. Ramirez-Laboreo, E. Moya-Lasheras, and C. Sagues, "Real-Time Electromagnetic Estimation for Reluctance Actuators," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 3, pp. 1952–1961, Mar. 2019. DOI: 10.1109/TIE.2018.2838077. Impact factor (JCR): 7.515, rank 1/64 (Q1).

[2] E. Moya-Lasheras, E. Ramirez-Laboreo, and C. Sagues, "Probability-Based Optimal Control Design for Soft Landing of Short-Stroke Actuators," *IEEE Transactions on Control Systems Technology*, vol. 28, no. 5, pp. 1956–1963, Sep. 2020, DOI: 10.1109/TCST.2019.2918479.

[3] E. Moya-Lasheras and C. Sagues, "Run-to-Run Control With Bayesian Optimization for Soft Landing of Short-Stroke Reluctance Actuators," *IEEE/ASME Transactions on Mechatronics*, vol. 25, no. 6, pp. 2645–2656, Dec. 2020. DOI: 10.1109/TMECH.2020.2987942.

[4] E. Moya-Lasheras, C. Sagues, and S. Llorente, "An Efficient Dynamical Model of Reluctance Actuators with Flux Fringing and Magnetic Hysteresis," *Mechatronics*, vol. 74, Apr. 2021. DOI: 10.1016/j.mechatronics.2021.102500.

[5] E. Moya-Lasheras, J. M. Schellekens, and C. Sagues, "Rauch–Tung–Striebel Smoother for Control of Short-Stroke Reluctance Actuators," under review.

International peer-reviewed conferences

[6] E. Moya-Lasheras, C. Sagues, E. Ramirez-Laboreo, and S. Llorente, "Nonlinear Bounded State Estimation for Sensorless Control of an Electromagnetic Device," in *2017 IEEE 56th Annual Conference on Decision and Control (CDC)*, Melbourne, Australia, Dec. 2017, pp. 5050–5055, DOI: 10.1109/CDC.2017.8264407.

[7] E. Moya-Lasheras, E. Ramirez-Laboreo, and C. Sagues, "A Novel Algorithm Based on Bayesian Optimization for Run-to-Run Control of Short-Stroke Reluctance Actuators," in *2019 18th European Control Conference (ECC)*, Naples, Italy, Jun. 2019, pp. 1103–1109, DOI: 10.23919/ECC.2019.8795949.

[8] E. Ramirez-Laboreo, E. Moya-Lasheras, and C. Sagues, "Optimal Open-Loop Control Policies for a Class of Nonlinear Actuators," in *2019 18th European Control Conference (ECC)*, Naples, Italy, jun 2019, pp. 3261–3266, DOI: 10.23919/ECC.2019.8795785.

[9] E. Moya-Lasheras, E. Ramirez-Laboreo, and C. Sagues, "Model-Free Sliding-Mode Controller for Soft Landing of Reluctance Actuators," *21st IFAC World Congress 2020*, Berlin, Germany, Jul. 2020.

Patent applications

[10] S. Llorente Gil, E. Moya Lasheras, E. J. Ramirez Laboreo, and C. Sagües Blázquiz, "Domestic appliance device," WO/2019/106488, 2019.

[11] J. Ballester Castañer, J. Corral Ricalde, S. Llorente Gil, E. Moya Lasheras, J. S. Ochoa Torres, E. Placer Maruri, E. J. Ramirez Laboreo, J. Rivera Peman, C. Sagües Blázquiz, and D. Serrano García, "Gas cooking appliance device," WO/2019/220247, 2019.