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An alternative to PIs and PIDs: Intelligent proportional-derivative regulators

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Summary

This paper suggests to replace PIs and PIDs, which play a key rôle in control engineering, by intelligent Proportional-Derivative feedback loops, or iPDs, which are derived from model-free control. This standpoint is enhanced by a laboratory experiment.

KEYWORDS:
Model-free control, intelligent proportional-derivative feedback (iPD), PI, PID, Riachy's trick.

1 | INTRODUCTION

Proportional-Integral-Derivative and Proportional-Integral regulators, or PIDs and PIs, are, as well-known, the most popular industrial feedback loops (see, *e.g.*, [6,7,19,20,42,44]). They ought therefore to be termed *universal*. Their serious shortcomings partly explain nevertheless the important developments of "modern" model-based control theory during the second half of the twentieth and the beginning of the twenty first centuries. In spite of beautiful achievements, PIs and PIDs still largely prevail in engineering. This paper aims to suggest a new universal feedback loop. It is derived from *Model-Free Control*, or *MFC*, in the sense of [15], *i.e.*, a control setting with two purposes:

- to keep the benefits of PIs and PIDs, and, especially, the futility of almost any mathematical modeling in control engineering;
- the deletion of many drawbacks of PIs and PIDs like, for instance, the devilish gain tuning difficulties or the lack of robustness.

The numerous successful concrete applications (see, *e.g.*, [9,15,17], and the corresponding bibliographies for references until the beginning of 2020) demonstrate that those aims have been fulfilled to a great extent. See, *e.g.*, the recent appraisal in [4]: "MFC is computationally efficient, easily deployable even on small embedded devices, and can be implemented in real time." Several conclusive concrete comparisons with PIs and PIDs have been published (see, *e.g.*, [2,3,8,13,22,27,29,35,39,41,43,46,54,55]).[1] Here we suggest a **single** universal feedback loop, *i.e.*, the *intelligent Proportional-Derivative* controller, or *iPD*,

$$u = -\frac{F_{\text{est}} - \ddot{y}^* + K_P e + K_D \dot{e}}{\alpha} \tag{1}$$

which is derived from the *ultra-local model* of order 2 in the sense of [15]

$$\ddot{y} = F + \alpha u \tag{2}$$

[1]Comparisons with several other control strategies have also been investigated (see, *e.g.*, [1,4,10,16,30,36,56,57,59,60]).

- u and y are the input and output variables.
- The time-varying quantity F corresponds to the poorly known plant and to the disturbances; F_{est} is an estimate of F.
- The constant α is chosen such that the three terms of Equation (2) are of the same magnitude.
- y^* is the reference trajectory.
- $e = y - y^*$ is the tracking error.
- The constants K_P and K_D are the gains.

Successful implementation of iPDs have already been achieved a number of times (see, *e.g.*,[8,10,23,26,38,52,53]):

- The gain tuning is straightforward.
- Recent algebraic parameter identification techniques[18,51] and Riachy's trick[47] permit to avoid tedious numerical derivations of the output signal y.
- Good robustness with respect to corrupting noises is ensured via a new noise understanding[14].

Until today MFC was offering not only the iPD (2) but also the *intelligent Proportional* controller, or (*iP*),

$$u = -\frac{F_{\text{est}} - \dot{y}^* + K_P e}{\alpha} \tag{3}$$

for the *ultra-local model* of order 1[15],

$$\dot{y} = F + \alpha u \tag{4}$$

Assume that "almost" any I/O system may be locally approximated by Equation (2), *i.e.*, by an ultra-local model of order 2. This postulate, which is the main conceptual novelty of our paper, is vindicated by fifteen years of MFC practice. It applies of course to a system which is well approximated by an ultra-local-model of order 1, *i.e.*, by Equation (4). The ubiquity of the iPD (1) follows at once. A laboratory experiment is presented in order to sustain this viewpoint. The Quanser AERO, *i.e.*, a half-quadrotor, is used as in two recent publications[17,34]: it is available at the *Université de Lorraine*. The results shows that adding an integrator deteriorates the behavior: intelligent Proportional-Integral-Derivative controllers, or iPIDs, might be useless.

Our paper is organized as follows. Basic facts on MFC are reviewed in Section 2. Riachy's trick[47] in particular, which plays a key rôle in the implementation of iPDs, is detailed in Section 2.4 for the first time since a conference communication ten years ago where it was only sketched. Section 3 is dedicated to the laboratory experiments. Concluding remarks and suggestions for future investigations are presented in Section 4.

2 | BASIC FACTS ON MODEL-FREE CONTROL

2.1 | Generalities

Elementary functional analysis and differential algebra permit to prove[15] that under quite weak assumptions any SISO system with input u and output y may be well approximated by

$$y^{(n)} = F + \alpha u \tag{5}$$

where

- the system might be infinite-dimensional and correspond to rather arbitrary functional equations and/or partial differential equations;
- $n \geq 1$ is the derivation order;
- the time-varying quantity F subsumes not only the un-modeled dynamics, but also the external disturbances;
- the constant $\alpha \in \mathbb{R}$ is such that the three quantities $y^{(n)}$, F, αu in Equation (5) are of the same order of magnitude.

Note that

- the poorly known plant is not necessarily of order n: $y^{(\nu)}$, where $\nu > n$ may be sitting in F;
- in all the numerous concrete case-studies that were encountered until now, $n = 1$ or 2;
- it is meaningless to try to estimate α precisely.

If $n = 2$, Equation (5) yields Equation (2). Associate to Equation (2) the *intelligent Proportional-Integral-Derivative* controller, or *iPID*,

$$u = -\frac{F_{\text{est}} - \ddot{y}^* + K_P e + K_I \int e + K_D \dot{e}}{\alpha} \tag{6}$$

where

- y^* is the reference trajectory,
- $e = y - y^*$ is the tracking error,
- K_P, K_I, K_D are tuning gains.

Equations (2) and (6) yield

$$\ddot{e} + K_D \dot{e} + K_P e + K_I \int e = F - F_{\text{est}} \tag{7}$$

Select K_P, K_I, K_D such that the roots of the characteristic equation

$$s^3 + K_D s^2 + K_P s + K_I = 0 \tag{8}$$

have strictly negative real parts. It ensures that $\lim_{t \to +\infty} e(t) \approx 0$ if the estimate F_{est} is "good," *i.e.*, $F - F_{\text{est}} \approx 0$. Thus *local stability* around the reference trajectory is trivially ensured via this feedback loop. Note that *global stability* is obviously difficult, if not impossible, to study without any mathematical modeling. Let us emphasize that the situation is much worse with classic PIs and PIDs where no stability property is available in general. The *intelligent Proportional-Derivative* controller (*iPD*) (1)) is obtained by setting $K_I = 0$. The *intelligent Proportional-Integral* (iPI) (resp. *intelligent Proportional* (*iP*)) controller corresponds to $K_D = 0$ (resp. $K_I = K_D = 0$).

The application of the Routh-Hurwitz[20,21,44] criterion to Equation (8) shows that the tuning of K_P and K_I alone does not permit to get arbitrary roots. It yields

Fact 1. If $n = 2$, iPs and iPIs do not work in general.

2.2 | An estimation integral

Take Equation (2). According to a a classic result of mathematical analysis (see, *e.g.*,[11]), F may be approximated, under a weak integrability condition, by a piecewise constant function. Replace therefore Equation (2) by

$$\ddot{y} = \Phi + \alpha u$$

where Φ is a constant. It yields via the rules of operational calculus (see, *e.g.*,[58])

$$s^2 Y = \frac{\Phi}{s} + U + s y(0) + \dot{y}(0)$$

In order to get rid of the initial conditions, derive both sides twice by $\frac{d}{ds}$:

$$\frac{2\Phi}{s^3} = s^2 \frac{d^2 Y}{ds^2} + 4s \frac{dY}{ds} + 2Y - \frac{d^2 U}{ds^2}$$

Multiplying both sides by s^{-N}, $N \geq 3$, permits to get rid of positive powers of s, *i.e.*, of time derivatives, which are very sensitive to corrupting noises. Negative powers of s, which correspond to iterated time integrals: noises are mitigated (see Remark 1 below). Thanks to the correspondance between $\frac{d}{ds}$ and the multiplication by $-t$, we get in the time domain for $N = 3$ (see, *e.g.*,[10,38])

$$F_{\text{est}}(t) = \frac{60}{\tau^5} \int_{t-\tau}^{t} (\tau^2 + 6\sigma^2 - 6\tau\sigma) y(\sigma) d\sigma - \frac{30\alpha}{\tau^5} \int_{t-\tau}^{t} (\tau - \sigma)^2 \sigma^2 u(\sigma) d\sigma \tag{9}$$

where $\tau > 0$ is "small."

Remark 1. According to[14] the robustness with respect to corrupting noises is ensured via the integrals in Equation (9). There is no need to know the precise probabilistic/statistical nature of the noises which are viewed as quick fluctuations around 0. See, *e.g.*,[40,51] for applications in signal processing.

Remark 2. In practice the integrals in Equation (9) are replaced by *finite impulse response* (*FIR*) filters (see, *e.g.*,[45]).

2.3 | iPs & PIs, iPD & PIDs

2.3.1 | PI & iP

Consider the PI regulator

$$u = k_p e + k_i \int e$$

where k_p, k_i are the gains. Derive both sides:

$$\dot{u}(t) = k_p \dot{e}(t) + k_i e(t)$$

A crude sampling yields:

$$\frac{u(t) - u(t-h)}{h} = k_p \frac{e(t) - e(t-h)}{h} + k_i e(t) \tag{10}$$

where h is the sampling period.

Replace F in Equation (3) by $\dot{y}(t) - \alpha u(t-h)$ and therefore by

$$\frac{y(t) - y(t-h)}{h} - \alpha u(t-h)$$

It yields

$$u(t) = u(t-h) - \frac{e(t) - e(t-h)}{h\alpha} + \frac{K_P}{\alpha} e(t) \tag{11}$$

Fact 2. Equations (10) and (11) become identical if we set

$$k_p = -\frac{1}{\alpha h}, \quad k_i = \frac{K_P}{\alpha h} \tag{12}$$

2.3.2 | PID & iPD

Consider the PID regulator

$$u = k_p e + k_i \int e + k_d \dot{e}$$

where k_p, k_i, k_d are the gains. Derive both sides: $\dot{u}(t) = k_p \dot{e}(t) + k_i e(t) + k_d \ddot{e}(t)$. It yields the obvious sampling

$$\frac{u(t) - u(t-h)}{h} = k_p \dot{e}(t) + k_i e(t) + k_d \ddot{e}(t) \tag{13}$$

Replace in Equation (2) F by $\ddot{y}(t) - \alpha u(t-h)$:

$$\frac{u(t) - u(t-h)}{h} = -\frac{1}{\alpha h} \ddot{e}(t) + \frac{K_P}{\alpha h} e(t) + \frac{K_D}{\alpha h} \dot{e}(t) \tag{14}$$

Fact 3. Equations (13) and (14) become identical if we set

$$k_p = \frac{K_D}{\alpha h}, \quad k_i = \frac{K_P}{\alpha h}, \quad k_d = -\frac{1}{\alpha h} \tag{15}$$

2.3.3 | Sampling and equivalence

The equivalences in Facts 2 and 3, which go back to[5,15], are strictly related to time sampling, *i.e.*, to the computer implementation, as demonstrated by taking $h \downarrow 0$ in Equations (12) and (15). In other words, the above equivalences do not hold in continuous-time. Those two facts nevertheless

1. explain the ubiquity in "real life" of PIs and PIDs,
2. explain the difficulty of gain tuning for PIs and PIDs,
3. question the necessity of introducing generalized PIDs (see, *e.g.*,[28,49]).

Remark 3. Formulae (12) and (15) should not be employed (compare with[25]) in order to deduce an iP (resp. a PI) from a PI (resp. an iP).

2.4 | Riachy's trick

Consider the ultra-local model (2) and the iPID (6). Following Riachy *et al.*[47] write

$$\ddot{y} + K_D \dot{y} = F + K_D \dot{y} + \alpha u \tag{16}$$

Set

$$Y(t) = y(t) + K_D \int_c^t y(\sigma) d\sigma \tag{17}$$

where $0 \leq c < t$. It yields

$$\ddot{Y} = \ddot{y} + K_D \dot{y}$$

Set

$$\mathfrak{F} = F + K_D \dot{y}$$

Equations (2)-(16) read

$$\ddot{Y} = \mathfrak{F} + \alpha u \tag{18}$$

The iPID (6) becomes

$$u = -\frac{\mathfrak{F}_{est} - \ddot{y}^* + K_P e + K_I \int_c^t e - K_D \dot{y}^*}{\alpha} \tag{19}$$

$\mathfrak{F}_{\text{est}}$ is given by (9) where y is replaced by Y. Set $K_I = 0$ in Equation (19) for the iPD. Riachy's trick permits to implement iPDs and iPIDs without estimating derivatives.

Remark 4. Resetting c in Equation (17) permits to trivially avoid any integral windup in Equations (17) and (19).

2.5 | The key postulate

Assume that almost any system encountered in practice, which is well approximated by Equation (5), where $n \geq 1$, may be also well approximated by Equation (2), *i.e.*, by an ultra-local model of order 2.

Remark 5. The determination of the lowest order n in Equation (5) seems to be a difficult mathematical question[33] which is far from being fully clarified. The above postulate shows that this question may be pointless from an applied standpoint.

3 | A LABORATORY EXPERIMENT

3.1 | Presentation

Employ as in[17,34] the *Quanser AERO* (see Figure 1), *i.e.*, a half-quadrotor, manufactured by the company Quanser (see the link `https://www.quanser.com/products/quanser-aero/`). Two motors driving the propellers, which might turn clockwise or not, are controlling the angular position y (rad) of the arms.

Write v_i, $i = 1, 2$, the supply voltage of motor i, where $-24\text{v} \leq v_i \leq 24\text{v}$ (volt). Introduce the single control variable u. Set

- if $u > 0$, then $v_1 = 10 + u$ and $v_2 = -10 - u$
- if $u < 0$, then $v_1 = -10 + u$ et $v_2 = 10 - u$

The sampling time interval is 10ms. The sample number for estimating integrals is 30.

After exhibiting as in[34] the performances of an iP, corresponding to a first order ultra-local model, we show that there is no degradation with an iPD associated to a second order ultra-local model. Let us emphasize that an iPID, which leads to oscillations, should be avoided.

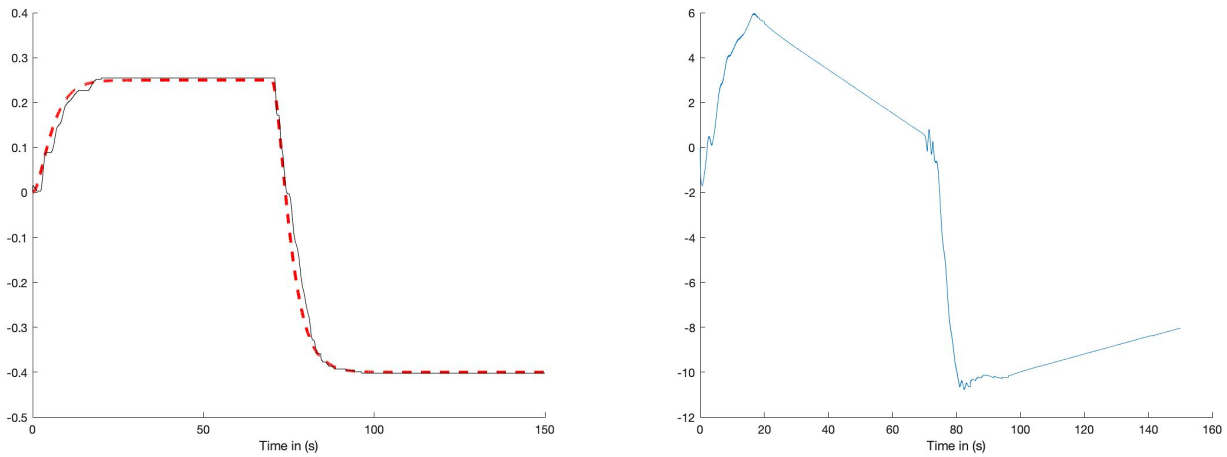
Remark 6. The experiments show, as outlined in Remark 1, a good robustness with respect to the unavoidable corrupting noises, among which the quantization noise is perhaps the most important one.

FIGURE 1 The Quanser AERO

3.2 | iP

Set in Equations (3)-(4) $\alpha = 10$, $K_P = 25$. Three scenarios are examined:

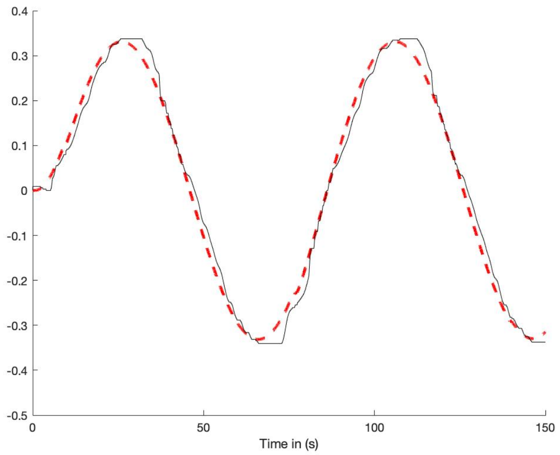
- **Scenario 1:** Figure 2 exhibits good performances with a rather simple reference trajectory.
- **Scenario 2:** With a more complex reference trajectory Figure 3 still displays good performances.
- **Scenario 3:** At $t = 15$s, disrupt now manually the system so that it rotates around the base axis. The corresponding centrifugal force should be seen as a perturbation. Figure 4 shows an excellent rejection.



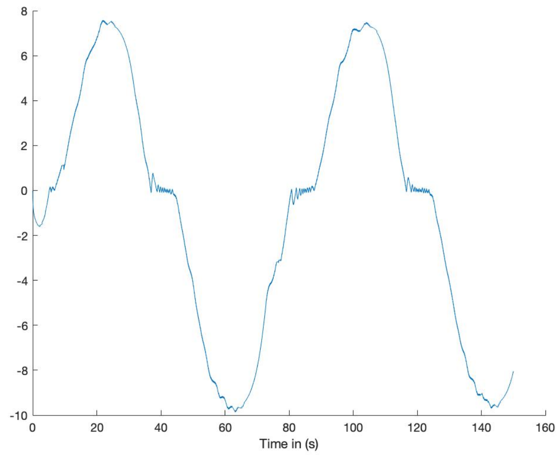
(a) Reference trajectory and position

(b) Control input

FIGURE 2 iP: Scenario 1

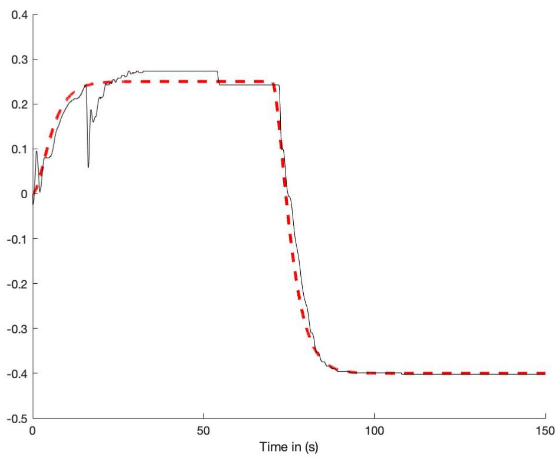


(*a*) Reference trajectory and position

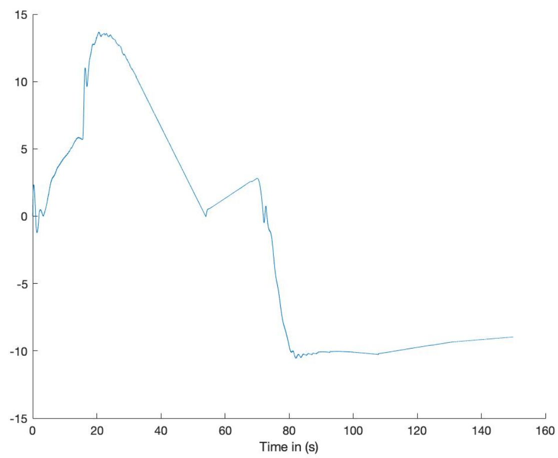


(*b*) Control input

FIGURE 3 iP: Scenario 2



(*a*) Reference trajectory and position



(*b*) Control input

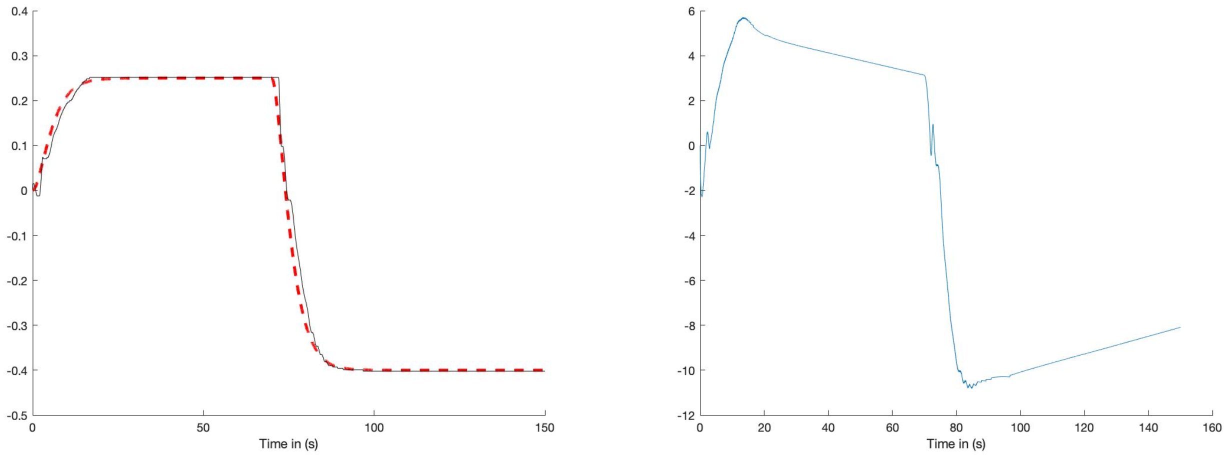
FIGURE 4 iP: Scenario 3

3.3 | iPD

Employ now with the same device a second order ultra-local model and an iPD. Set $\alpha = 10$, $K_P = 25$, $K_D = 10$ in Equations (1)-(2). Figures 5, 6, 7 display the performances with respect to scenarios 4, 5, and 6, which are the analogues of scenarios 1, 2, and 3 in Section 3.2. The results are similar to those in Section 3.2: they are again excellent.

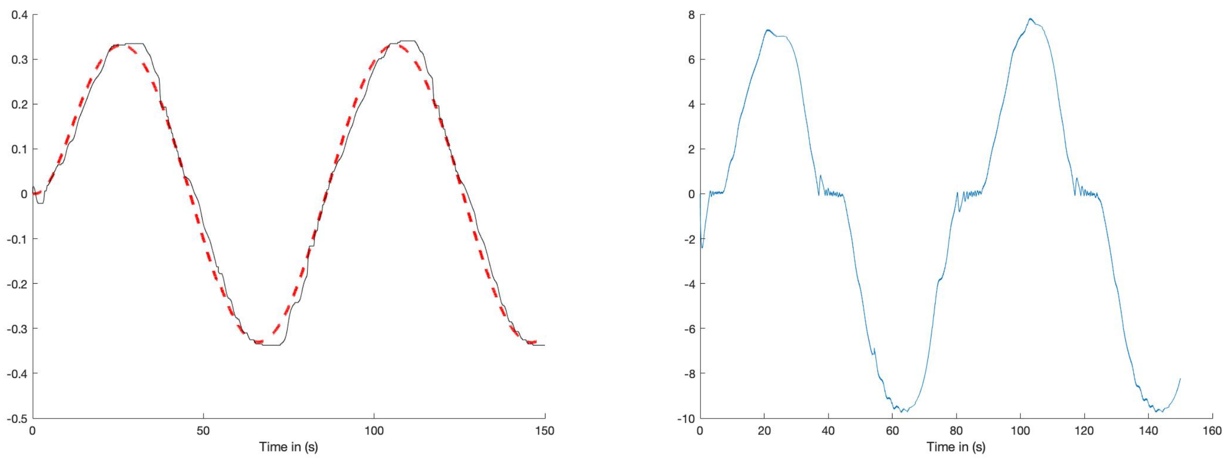
3.4 | iPID

With respect to the iPD (6), the scenarios 7, 8, and 9, which are displayed by Figures 8, 9, and 10, are the analogues of scenarios 1 and 4 in Sections 3.2 and 3.3. The coefficient $\alpha = 10$, the gains $K_P = 25$ and $K_D = 10$ are the same as in Section 3.3. Performances deteriorate when the gain K_I increases "too much."



(a) Reference trajectory and position *(b)* Control input

FIGURE 5 iPD: Scenario 4



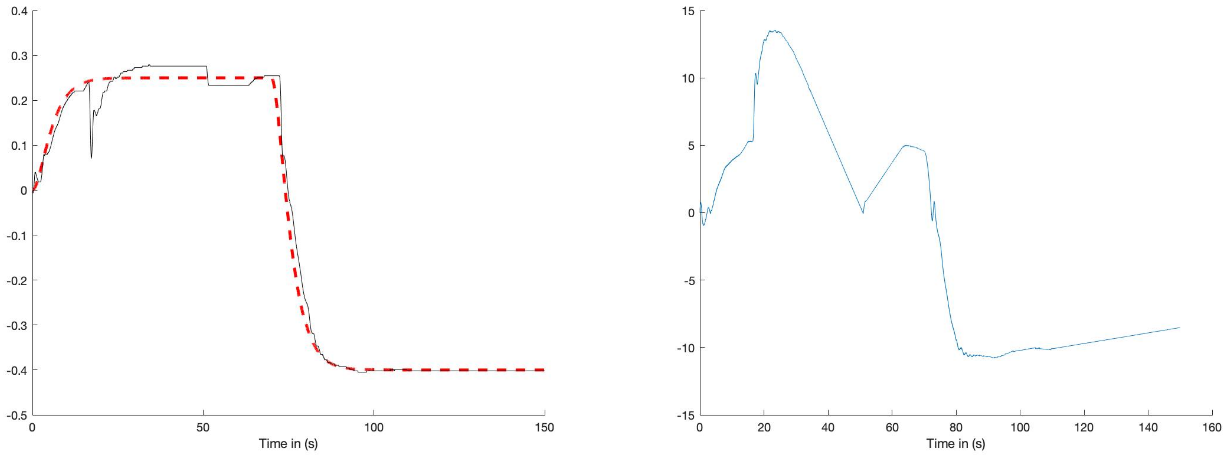
(a) Reference trajectory and position *(b)* Control input

FIGURE 6 iPD: Scenario 5

4 | CONCLUSION

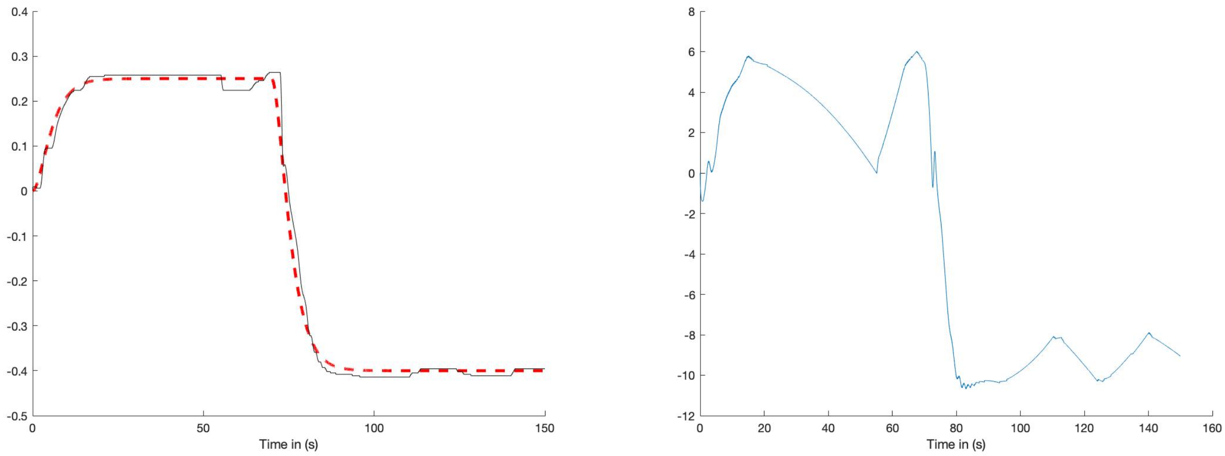
In order to be fully accepted the proposed replacement of traditional PIs and PIDs by iPDs needs of course further confirmations via many concrete case-studies. If this is the case, several investigations ought to be carried on. Let us mention here:

- The determination of the coefficient α in Equation (2) should be better analyzed. See [17] for a first hint.
- The impossibility of ensuring global stability in the context of model-free control should be replaced by a suitable replanning of the reference trajectory (see, *e.g.*, [12] for a replanning example in the context of flatness-based control).
- The extension to iPDs of the hardware for iPs in [32].
- The extension of the treatment of multi-input multi-output (MIMO) systems in [36].



(a) Reference trajectory and position *(b)* Control input

FIGURE 7 iPD: Scenario 6

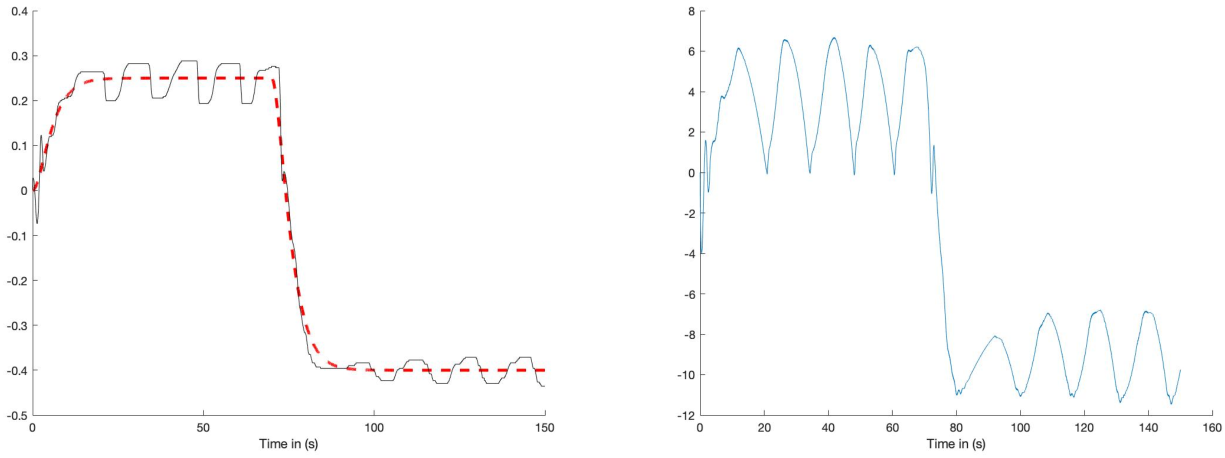


(a) Reference trajectory and position *(b)* Control input

FIGURE 8 iPID: Scenario 7 ($K_I = 0.001$)

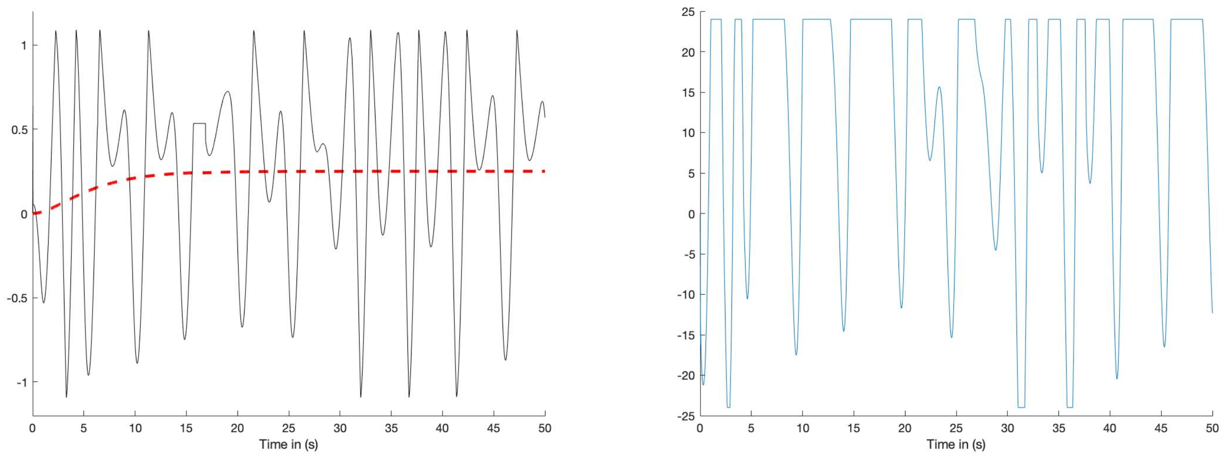
- The extension to the discrete-time approach in[48].
- A more thorough study of iPIDs in order to determine possible benefits with respect to iPDs.[2]
- The regulation via PIDs of systems with delays is far from being fully understood (see, *e.g.*,[37,50]). It would be rewarding to extend, if possible, the time series setting in[24] for supply chain management.
- The approach to machine learning sketched in[17] should benefit from the unicity of the feedback loop advocated here. See also[48].

[2]Would for instance the most convincing application[31] to an electromagnetic robot, where an iPID is employed, be improved or not by an iPD?



(a) Reference trajectory and position *(b)* Control input

FIGURE 9 iPID: Scenario 8 ($K_I = 0.01$)



(a) Reference trajectory and position *(b)* Control input

FIGURE 10 iPID: Scenario 9 ($K_I = 0.1$)

References

1. A.B.O. Abbaker, H. Wang, Y. Tian. Voltage control of solid oxide fuel cell power plant based on intelligent proportional integral-adaptive sliding mode control with ant-windup compensator. *Trans. Inst. Measur. Contr.*, 42, 116-130, 2020.

2. J.T. Agee, Z. Bingul, S. Kizir. Tip trajectory control of a flexible-link manipulator using an intelligent proportional integral (iPI) controller. *Trans. Inst. Measur. Contr.*, 36, 673-682, 2014.

3. J.T. Agee, S. Kizir, Z. Bingul. Intelligent proportional-integral (iPI) control of a single link flexible joint manipulator. *J. Vibr. Contr.*, 21, 2273-2288, 2015.

4. K. Amasyali, Y. Chen, B. Telsang, M. Olama, S. Djouadi. Hierarchical model-free transactional control of building loads to support grid services. *IEEE Access*, 8, 219367-219377, 2020.

5. d'Andréa-Novel, M. Fliess, C. Join, H. Mounier, B. Steux. A mathematical explanation via "intelligent" PID controllers of the strange ubiquity of PIDs. *18th Medit. Conf. Contr. Automat.*, Marrakech, 2010. `https://hal.inria.fr/inria-00480293/en/`

6. K.J. Åström, T. Hägglund. *Advanced PID Control*. Instrument Soc. Amer., 2006.

7. K.J. Åström, R.M. Murray. *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton University Press, 2008.

8. A. Baciu, C. Lazar. Model free speed control of spark ignition engines. *23rd Int. Conf. Syst. Theor. Contr. Computing*, Sinaia, 2019

9. O. Bara, M. Fliess, C. Join, J. Day, S.M. Djouadi. Toward a model-free feedback control synthesis for treating acute inflammation. *J. Theoret. Biology*, 448, 26-37, 2018.

10. J.M.O. Barth, J.-P. Condomines, M. Bronz, J.-M. Moschetta, C. Join, M. Fliess. Model-free control algorithms for micro air vehicles with transitioning flight capabilities. *Int. J. Micro Air Vehic.*, 12, 2020 `doi:10.1177/1756829320914264`

11. N. Bourbaki. *Fonctions d'une variable réelle*. Hermann, 1976. English translation: *Functions of a Real Variable*. Springer, 1994.

12. A. Chamseddine, D. Theilliol, Y.M. Zhang, C. Join, C.A. Rabbath. Active fault-tolerant control system design with trajectory re-planning against actuator faults and saturation: Application to a quadrotor unmanned aerial vehicle. *Int. J. Adapt. Contr. Sign. Process.*, 29, 1-23, 2015.

13. M. Clouatre, M. Thitsa, M. Fliess, C. Join. A robust but easily implementable remote control for quadrotors: Experimental acrobatic flight tests. *Int. Conf. Advanc. Techno.*, Istanbul, 2020. `https://hal.archives-ouvertes.fr/hal-02910179/en/`

14. M. Fliess. Analyse non standard du bruit. *C.R. Acad. Sci. Paris Ser. I*, 342, 797-802, 2006.

15. M. Fliess, C. Join. Model-free control. *Int. J. Contr.*, 86, 2228-2252, 2013.

16. M. Fliess, C. Join. Deux améliorations concurrentes des PID. *ISTE Automat./Contr.*, 2, 23 pages. `https://hal.archives-ouvertes.fr/hal-01687952/en/`

17. M. Fliess, C. Join. Machine learning and control engineering: The model-free case. In: K. Arai, S. Kapoor, R. Bhatia (eds) *Proceedings of the Future Technologies Conference (FTC) 2020*, Advances in Intelligent Systems and Computing, vol 1288. Springer, 2021. `https://hal.archives-ouvertes.fr/hal-02851119/en/`

18. M. Fliess, H. Sira-Ramírez. Closed-loop parametric identification for continuous-time linear systems via new algebraic techniques. H. Garnier & L. Wang (Eds): *Identification of Continuous-time Models from Sampled Data*, Springer, pp. 362-391, 2008.

19. O. Föllinger, F. Dörrscheidt, M. Klittich. *Regelungstechnik* (10. Auflage). Hüthig, 2008..

20. G.F. Franklin, J.D. Powell, A. Emami-Naeini. *Feedback Control of Dynamic Systems* (8th ed.). Pearson, 2019.

21. F.R. Gantmacher. *The Theory of Matrices*, vol. 1 & 2 (translated from the Russian). Chelsea, 1959.

22. P.-A. Gédouin, E. Delaleau, J.-M. Bourgeot, C. Join, S. Arbab Chirani, S. Calloch. Experimental comparison of classical PID and model-free control: Position control of a shape memory alloy active spring. *Contr. Engin. Pract.*, 19, Pages 433-441, 2011.

23. M. Haddar, R. Chaari, S. Caglar Baslamisli, F. Chaari, M. Haddar. Intelligent PD controller design for active suspension system based on robust model-free control strategy. *J. Mech. Engin. Sci.*, 233, 4863-4880, 2019.

24. K. Hamiche, M. Fliess, C. Join, H. Abouaïssa. Bullwhip effect attenuation in supply chain management via control-theoretic tools and short-term forecasts: A preliminary study with an application to perishable inventories. *6th Int. Conf. Contr. Deci. Informat. Techno.*, Paris, 2019. `https://hal.archives-ouvertes.fr/hal-02050480/en/`

25. W. Han, G. Wang, A.M. Stankovic. Active disturbance rejection control in fully distributed automatic generation control with co-simulation of communication delay. *Contr. Engin. Pract.*, 85, 225-234, 2019.

26. S. Han, H. Wang, Y. Tian. A linear discrete-time extended state observer-based intelligent PD controller for a 12 DOFs lower limb exoskeleton LLE-RePA. *Mech. Syst. Sign. Process.*, 138, 106547, 2020.

27. Y. Hong, D. Xu, W. Yang, B. Jiang, X.-G. Yan. A novel multi-agent model-free control for state-of-charge balancing between distributed battery energy storage systems. *IEEE Trans. Emerg. Topic. Comput. Intel.*, 2020. DOI: 10.1109/TETCI.2020.2978434

28. M. Huba, D. Vrancic, P. Bistak. PID control with higher order derivative degrees for IPDT plant models. *IEEE Access*, 9, 2478-2495, 2020.

29. F. Hugo Ramírez Leyva, E. Yescas Mendoza, E. Peralta Sánchez, Á. Jesús Mendoza Jasso, F. Iturbide Jiménez. Control libre de modelo de un convertidor CD-CD buck y su implementación en la plataforma de hardware in the loop 'Thyphoon". *Memor. Congr. Nacion. Contr. Autom.*, Puebla, 2019.

30. M.A. Jama, H. Noura, A. Wahyudie, A. Assi. Enhancing the performance of heaving wave energy converters using model-free control approach. *Renew. Ener.*, 83, 931-941, 2015.

31. J.-H. Jeong, D.-H. Lee, M. Kim, W.-H. Park, G.-S. Byun, S.-W. Oh. The study of the electromagnetic robot with a four-wheel drive and applied I-PID system. *J. Electr. Eng. Technol.*, 12, 1634-1640, 2017.

32. C. Join, F. Chaxel, M. Fliess. "Intelligent" controllers on cheap and small programmable devices. *2nd Int. Conf. Contr. Fault-Tolerant Syst.*, Nice, 2013. https://hal.archives-ouvertes.fr/hal-00845795/en/

33. C. Join, E. Delaleau, M. Fliess, C.H. Moog. Un résultat intrigant en commande sans modèle. *ISTE OpenSci. Automat./Contr.*, 1, 9 pages, 2017. https://hal.archives-ouvertes.fr/hal-01628322/en/

34. C. Join, M. Fliess, F. Chaxel. Model-free control as a service in the Industrial Internet of Things: Packet loss and latency issues via preliminary experiments. *28th Med. Conf. Contr. Automat.*, Saint-Raphaël, 2020 https://hal.archives-ouvertes.fr/hal-02546750/en/

35. S. Kizir, Z. Bingül. Design and development of a Steward platform assisted and navigated transsphenoidal surgery. *Turk. J. Elect. Eng. Comp. Sci.*, 27, 961-972, 2019.

36. F. Lafont, J.-F. Balmat, N. Pessel, M. Fliess. A model-free control strategy for an experimental greenhouse with an application to fault accommodation. *Comput. Electron. Agricul.*, 110, 139-149, 2015.

37. D. Ma, J. Chen, A. Liu, J. Chen, S.-I. Niculescu. Explicit bounds for guaranteed stabilization by PID control of second-order unstable delay systems. *Automatica*, 100, 407-411, 2019.

38. L. Menhour, B. d'Andréa-Novel, M. Fliess, D. Gruyer, H. Mounier. An efficient model-free setting for longitudinal and lateral vehicle control: Validation through the interconnected Pro-SiVIC/RTMaps prototyping platform. *IEEE Trans. Intel. Transport. Syst.*, 19, 461-475, 2018.

39. L. Michel, C. Join, M. Fliess, P. Sicard, A. Chériti. Model-free control of dc/dc converters. *IEEE 12th Worksh. Contr. Model. Power Electron.*, Boulder, 2010. https://hal.inria.fr/inria-00495776/en/

40. R. Morales, E. Segura, J.A. Somolinos, L.R. Núñez, H. Sira-Ramírez. Online signal filtering based on the algebraic method and its experimental derivation. *Mech. Syst. Sign. Proc.*, 66-67, 374-387, 2016.

41. I. N'Doye , S. Asiri, A. Aloufi, A. Al-Awan, T.-M. Laleg-Kirati. Intelligent proportional-integral-derivative control-based modulating functions for laser beam pointing and stabilization. *IEEE Trans. Contr. Syst. Techno.*, 28, 1001-1008, 2020.

42. A. O'Dwyer. Handbook of PI and PID Controller Tuning Rules (3rd ed.). Imperial College Press, 2009.

43. B. Park, M.M. Olama. A model-free voltage control approach to mitigate motor stalling and FIDVR for smart grids. *IEEE Trans. Smart Grid*, 12, 2021.

44. P. Prouvost. *Automatique – Contrôle et régulation* (2^e éd.). Dunod, 2010.

45. L.R. Rabiner, B. Gold. *Theory and Application of Digital Signal Processing*. Prentice-Hall, 1975.

46. M. Rampazzo, D. Tognin, M. Pagan, L. Carniello, A. Beghi. Modelling, simulation and real-time control of a laboratory tide generation system. *Contr. Engin. Pract.*, 83, 165-175, 2019

47. S. Riachy, M. Fliess, C. Join. High-order sliding modes and intelligent PID controllers: First steps toward a practical comparison. *18th World Congr. IFAC*, Milano, 2011. `https://hal.archives-ouvertes.fr/hal-00580970/en/`

48. A.K. Sanyal. Discrete-time data-driven control with Hölder-continuous real-time learning. *Int. J. Contr.*, 2021. `DOI: 10.1080/00207179.2021.1901993`

49. P. Shah, S. Agashe. Review of fractional PID controllers. *Mechatron.*, 38, 29-41, 2016.

50. G. J. Silva, A. Datta, S. P. Bhattacharyya. *PID controllers for time-delay systems*. Birkhäuser, 2005.

51. H. Sira-Ramírez, C. García-Rodríguez, J. Cortès-Romero, A. Luviano-Juárez. *Algebraic Identification and Estimation Methods in Feedback Control Systems*. Wiley, 2013.

52. J. Sun, J. Wang, P. Yang, S. Guo. Model-free prescribed performance fixed-time control for wearable exoskeletons. *Appl. Math. Model.*, 90, 61-77, 2021.

53. M. Ticherfatine, Q. Zhu. Fast ferry smoothing motion via intelligent PD controller. *J. Marin. Sci. App.*, 17, 273-279, 2018.

54. J. Villagra, C. Balaguer. A model-free approach for accurate joint motion control in humanoid locomotion. *Int. J. Human. Robot.*, 8, 27-46, 2011.

55. J. Villagra, C. Join, R. Haber, M. Fliess. Model-free control for machine tools. 21st IFAC World Congress, Berlin, 2020. `https://hal.archives-ouvertes.fr/hal-02568336/en/`

56. J. Wang, H. Mounier, S.-I. Niculescu, M.-S. Geamanu. Event-driven model-free control in motion control with comparisons. *IMA J. Math. Contr. Informat.*, 34, 1255-1275, 2017.

57. H. Yang, C. Liu, J. Shi, G. Zheng. Development and control of four-wheel independent driving and modular steering electric vehicles for improved maneuverability limits. *SAE Techn. Pap.*, 2019-01-0459, 2019. `https://doi.org/10.4271/2019-01-0459`

58. K. Yosida. *Operational Calculus* (translated from the Japanese). Springer, 1984.

59. Y. Zhang, X. Liu, J. Liu, J. Rodriguez, C. Garcia. Model-free predictive current control of power converters based on ultra-local model. *IEEE Int. Conf. Indust. Techno.*, Buenos Aires, 2020.

60. Y. Zhang, T. Jiang, J. Jiao. Model-free predictive current control of a DFIG using an ultra-local model for grid synchronization and power regulation. *IEEE Trans. Energ. Conver.*, 35, 2269-2280, 2020.

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