Intelligent Proportional-Integral-Derivative Control based Modulating Functions for Laser Beam Pointing and Stabilization

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Abstract—This paper studies the problem of high-precision positioning of laser beams using an intelligent proportional-integral-derivative controller. The control problem addressed in laser beams aims at maintaining the position of the laser beam on a position sensing device under the effects of noise and active disturbances. The design of an intelligent proportional-integral-derivative control is based on the so called ultra-local system description. The intelligent proportional-integral-derivative controller has been implemented and validated on a real test bench. For the sake of enhancing the performance of the closed loop, it has been combined with a non-asymptotic and robust modulating function-based estimation method, which is used to estimate the un-modeled dynamics and disturbances. The proposed intelligent proportional-integral-derivative controller has shown good performance in handling the active disturbances and uncertainties present in the platform. A comparison to the classical proportional-integral-derivative and robust proportional-integral-derivative is also provided based on the experimental set-up. Robustness tests are performed experimentally to show the effectiveness of the intelligent proportional-integral-derivative control.

Index Terms—Laser beams, proportional-integral-derivative control, robust proportional-integral-derivative control, model-free control, intelligent proportional-integral-derivative control, modulating functions.

I. INTRODUCTION

Laser is a device that emits a beam of light by stimulated emission of photons from excited atoms or molecules. It has been used in different applications such as communication, surgeries, printing, bar code scanning, laser cutting and many other applications. The need for high accuracy pointing is considered as a big challenge for these systems and especially in presence of vibrations of the pointing system or under external disturbances [1]. The objective of this paper is to design a robust controller for laser beam stabilization and pointing which reduces the effect of active disturbances, the main source of pointing errors.

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Several control techniques such as proportional-integral-derivative (PID) and robust proportional-integral-derivative (RPID) controllers [1], [2], passive control [3]–[5], adaptive control techniques or more advanced adaptive techniques [6]–[11] have been combined with feedback and/or feedforward controllers, estimation and/or identification methods. PID controllers with a beam-stabilized optical switch have been proposed in [2], [12] to stabilize a beam at a desired angle and maximize the optical power detected by a photodiode using a voice-coil motor actuator. Recently, a Fractional-Order PID (FOPID) controller has been implemented on a laser beam positioning system [13] and has been compared to classical PID controllers. This study has shown that the FOPID controller provides excellent stabilization properties with minimal switching time and good robustness with respect to moderate disturbances. However the FOPID needs fine tuning to deal with strong vibration conditions of the pointing systems.

In this study, intelligent proportional-integral-derivative (i-PID) controller is introduced as an alternative robust control strategy to the PID control [14]–[16]. The conventional PID controller is one of the most used controller in industry for closed control-loops thanks to its simplicity in real time implementation. The design and tuning of such a controller has been widely covered and is still an active field of research especially for industrial plants subject to external disturbances (see [14], [16], [17]). Indeed, due to the significant variations in the amplitude vibration affected by the external disturbances, satisfactory performance covering the total range of disturbances is difficult to reach with a conventional PID without an external compensation. Thereafter, it is desirable to design robust control strategies without additional complexity and computational effort. To take into consideration model's uncertainties and modeling errors when designing a controller, model-free control (MFC) algorithm has been proposed in [18], [19]. The main feature of this approach consists in updating continuously the input-output behavior using an ultra-local-model. This allows the compensation of modeling errors, system uncertainties, disturbances and actuator faults. In [18], MFC has been combined to a standard PID controller to make the intelligent PID controller (i-PID). In addition to being very simple to implement, i-PID controller is robust with respect to system's uncertainties, modeling errors and disturbances (see, e.g., [19]). MFC in general and i-PID in particular have been considered in several applications such as: shape memory alloys [20], DC/DC converters [21],

active magnetic bearing [22], two-dimensional planar manipulator [23], agricultural greenhouse [24], quadrotor vehicle and aerospace [25]–[28], automotive engine [29], mechanical system [30] and references therein. The system uncertainties and the modeling errors that represent the overall time-varying dynamics in MFC uses a derivative operation on the output system. However, differentiating the output system, which is usually noisy, amplifies the noise. This paper proposes to implement modulating function-based method (MFBM) for the estimation of the effects of the overall time-varying dynamics. MFBM has been introduced in the early 1950s [31] and has been used in parameters identification for ordinary differential equations. Later, the method has been extended to estimate input, states, varying coefficients in ordinary, partial and fractional differential equations [32]–[34]. The MFBM simplifies the problem into a system of algebraic equations linear in unknown parameters. Moreover, it is designed based on the differential equation without reliance on model approximation, which reduces the information loss. Furthermore, its filtering property makes this method robust, and hence interesting in several real processes. The features of the MFBM are similar to those in algebraic estimation methods [35]. In addition, the MFBM can be considered as a generalization of the algebraic estimation methods in some cases (see, e.g., [36]–[41]).

The contributions of the paper are as follows:

- We design an i-PID control to reduce the active disturbance and minimize dynamic laser beam pointing errors.
- The performance of i-PID is evaluated by comparison to the robust and conventional PID controllers through real-time experiments.
- Robustness analysis is performed and validated with respect to exogenous disturbance, parameter uncertainty and disturbance rejection through experiments.
- The performance of the i-PID control is enhanced by estimating the unmodeled dynamics and disturbance effects of the laser beam system using the MFBM.

II. PRELIMINARIES

This section gives some preliminaries about ultra local model and the modulating functions method.

A. Ultra local model

The MFC is based on ultra-local model that is continuously updated according to the input-output behavior of a system. It is designed to overcome the unmodeled dynamics and uncertainties of the system, especially in the case of nonlinear system. The MFC was already applied and used quite successfully in various applications [19], [25]–[30], [36], [37]. The MFC is based on the following ultra-local description

$$y^{(\nu)}(t) = F(t) + \alpha u(t), \quad (1)$$

where F represents the effects of un-modeled dynamics and disturbances, it is estimated using the information from the control input u and the controlled output y . α is a normalization factor and chosen such that αu and $y^{(\nu)}$ are of the same order of magnitude. ν is the differentiation order.

Remark 1: The value of ν usually depends on prior knowledge on the system stability and the nature of the control

Fig. 1. Laser beam stabilization principle

input. It may also depend on its relative degree. Indeed, studies have shown that with the i-PID and intelligent Proportional Derivative (i-PD) controllers the value $\nu = 2$ is suitable while for the intelligent Proportional Integral (i-PI) and the intelligent Proportional (i-P) a value $\nu = 1$ works better [26].

B. Modulating Function-Based Method

Definition 1: A function $\phi(t) \neq 0$ is called a modulating function of order l ($l \in \mathbb{N}^*$) on $[0, T]$ if it satisfies:

$$\begin{cases} \phi(t) \in C^l([0, T]), \\ \phi^{(p)}(0) = \phi^{(p)}(T) = 0, \quad p = 0, 1, \dots, l-1 \end{cases} \quad (2a)$$

$$\quad (2b)$$

where $T > 0$ and p refers to the order of the derivative.

The MFBM for parameter estimation follows the following four main steps:

- Step 1: The differential equation is multiplied by a set of modulating functions.
- Step 2: The resulting differential equations are integrated over the time interval. The integration contributes in filtering and attenuating the noise.
- Step 3: Integration by parts formula is applied on the integral equations to transfer the derivatives from the noisy measurements to the modulating functions, which are smooth enough.
- Step 4: The obtained equations are formulated into an algebraic linear system for which the solution provides an estimate of the unknown parameters.

For more details about the method, the reader can refer to [33] and the references therein.

III. SYSTEM DESCRIPTION

The principle of laser beam stabilization is presented in Fig. 1. The laser beam source is subject to various disturbances. A fast-steering mirror (FSM) which rotates about a pivot reflects the beam to a beam splitter. The beam is then directed to the target but part of it is directed to a position sensing detector (PSD). The mechanism is mounted on a spring-loaded linear slide that is free to oscillate along one axis. Turning on the motor, oscillations occur and induces undesired vibrations (disturbances) on the FSM and consequently in the beam position. PSD measures how far the beam has displaced from the target. Then the control system sends signal to the FSM such that the beam remains stable on the target. The length of detectable surface is 10 mm.

Fig. 2. Schematic diagram of i-PID model-free control of laser beam plant.

The transfer function of the open-loop voltage-to-position of the system is given as follows [1]:

$$P(s) = \frac{K}{s(Ts + 1)} \quad (3)$$

where $K = 2200 \text{ mm/(Vs)}$ is the open-loop steady-state gain and $T = 0.005 \text{ s}$ is the open-loop time constant.

IV. INTELLIGENT PID BASED MODULATING FUNCTION CONTROLLER

A. Intelligent PID controller

In this paper, the differentiation order ν of the ultra local model is fixed to 2. This is because an i-PID controller is used in the laser beam control system (3) according to the system stability. Setting $\nu = 2$ in equation (1), we have

$$\ddot{y}(t) = F(t) + \alpha u(t). \quad (4)$$

Hence, the corresponding i-PID can be written as

$$u(t) = -\frac{(\hat{F}(t) - \ddot{y}^d(t) + K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \dot{e}(t))}{\alpha} \quad (5)$$

where

- y^d is the desired reference trajectory,
 - $\hat{F}$ is the estimate of F which is described as follows,
- $$\hat{F}(t) = \ddot{\hat{y}}(t) - \alpha u(t), \quad (6)$$
- $\hat{y}$ is the estimate of y ,
 - $e(t) = y(t) - y^d(t)$ is the trajectory tracking error,
 - K_P , K_I and K_D are the PID gains.

Once $\hat{F}$ is obtained, the loop is closed by (5) and the modified expression of (4) is given as (6).

Fig. 2 depicts the model-free control scheme for the laser beam stabilizer. As illustrated by Fig. 2, the ultra-local model in (6) will compute the value of $\hat{F}$ on every iteration of the closed loop controller. The updated value will inject a proper change in the control input of the laser beam plant. Substituting equation (6) in (5), adding and subtracting the derivate of the controlled output $\ddot{y}$ yields

$$\ddot{e}(t) + K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \dot{e}(t) = e_F(t), \quad (7)$$

where $e_F(t) = \ddot{y}(t) - \ddot{\hat{y}}(t) = F(t) - \hat{F}(t)$. Subsequently, with a good estimate $\hat{F}(t)$ of $F(t)$ i.e $e_F(t) = F(t) - \hat{F}(t) \simeq 0$, equation (7) yields

$$\ddot{e}(t) + K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \dot{e}(t) \simeq 0, \quad (8)$$

which ensures an excellent tracking of the reference trajectory. This tracking is moreover quite robust with respect

to uncertainties and disturbances, which can be important in a laser beam pointing and stabilization setting such as considered here. This robustness feature is explained by the fact that F includes all the effects of un-modeled dynamics and disturbances, without trying to distinguish between its different components. Furthermore, the approximation of the PID's design parameters becomes therefore quite straightforward. This is an important advantage when compared to the standard PID.

B. Modulating function-based i-PID controller

The estimation of F which represents the overall estimate time-varying disturbance effects of the system is obtained thanks to the knowledge of the input and the controlled output derivatives. Due to the fact that output signal could be infected by substantial amount of noise, differentiating that signal might not be suitable in most concrete situations. In this paper, the MFBM is used to online estimate the effects of un-modeled dynamics and disturbances. Thanks to the advantages of the MFBM, the derivatives from the noisy measurements are transferred to the modulating functions, consequently, differentiating noisy measurements is avoided. It is worth noting that the involved integrals from MFBM can work as a noise filter to reduce the effect of the random disturbances on the estimation of F . Subsequently, the online estimate value F will ensure a proper change in the control input of the laser beam plant.

To estimate F while the system is operating, a moving-horizon strategy is applied [38]. The main idea of this strategy is to implement the MFBM on a time window that moves one sampling time forward. That is, F is estimated on $[k\Delta t, \tau + k\Delta t]$, $k = 0, 1, \dots$, where Δt and τ refer to the sampling time and the window size, respectively; then the control u is updated at a future time instant based on the last estimated F . More details are given in the following theorem.

Theorem 1: Let $\sum_{i=1}^I \gamma_i \xi_i(t)$ be a basis expansion of $F(t)$

in (4) where $\xi_i(t)$ and γ_i , for $i = 1, \dots, I$, are polynomial basis functions and basis coefficients, respectively. Let $\Phi^M = \{\phi_m(t)\}_{m=1}^{m=M}$ be a class of linearly independent polynomial modulating functions with $M \geq I$. Then, the unknown coefficients γ_i , $i = 1, 2, \dots, I$, can be estimated at each window $[k\Delta t, \tau + k\Delta t]$, $k = 0, 1, \dots$, by solving the system:

$$\mathcal{A}\Gamma = \mathcal{K}, \quad (9)$$

where the components of the $M \times I$ matrix $\mathcal{A}$ have the following form:

$$\mathcal{A}_{mi} = \int_{k\Delta t}^{\tau+k\Delta t} \xi_i(t) \phi_m(t) dt, \quad (10)$$

for $m = 1, \dots, M$ and $i = 1, \dots, I$; the components of the vector $\mathcal{K} \in \mathbb{R}^M$ are given as:

$$\mathcal{K}_m = \int_{k\Delta t}^{\tau+k\Delta t} y(t) \ddot{\phi}_m(t) - \alpha u(t) \phi_m(t) dt, \quad (11)$$

and Γ is the vector of the unknowns γ_i , $i = 1, \dots, I$.

Fig. 3. Laboratory plant

Proof 1: First, equation (4) is multiplied by $\phi_m(t)$ and integrated over the window $[k\Delta t, \tau + k\Delta t]$:

$$\int_{k\Delta t}^{\tau+k\Delta t} F(t)\phi_m(t) dt = \int_{k\Delta t}^{\tau+k\Delta t} \ddot{y}(t)\phi_m(t) dt - \int_{k\Delta t}^{\tau+k\Delta t} \alpha u(t)\phi_m(t) dt. \quad (12)$$

Then, applying integration by parts formula to the first term in the right-hand side of (12), one can obtain

$$\int_{k\Delta t}^{\tau+k\Delta t} F(t)\phi_m(t) dt = \int_{k\Delta t}^{\tau+k\Delta t} y(t)\ddot{\phi}_m(t) dt - \alpha \int_{k\Delta t}^{\tau+k\Delta t} u(t)\phi_m(t) dt. \quad (13)$$

Finally, using the basis expansion of $F(t)$, one can write $F(t) = \sum_{i=1}^I \gamma_i \xi_i(t)$; hence, system (9) is obtained with components as in (10) and (11).

V. EXPERIMENTAL RESULTS

This section shows real-time experimental results of the standard i-PID controller using Simulink differentiator block (SDB) and of the combined i-PID controller and MFBM.

The laboratory plant used in this work is a laser beam stabilizer system shown in Fig. 3. The plant is conveniently connected to the PC via Quanser Personality Intelligent Data (QPID) acquisition board and Peripheral Component Interconnect (PCI) board for data transfer. MATLAB/Simulink library for real-time control of the plant which uses the WinCon application from Quanser, to communicate with the data acquisition card is available [1].

Different components form the laser beam stabilization system; a stationary laser source provides the laser beam, a FSM acts as a voice coil mounted on a vibrating platform, a DC motor which generates an active disturbance and an amplifier provides the voltage or maximum power to the actuator by the Digital-to-Analog convertor (D/A) and also increases the signal from the position sensing device to the Analog-to-Digital converter. There is also a data acquisition board QPID which acts also as a Digital-to-Analog-to-Digital convertor (D-A-D) [1].

A. Intelligent PID controller

This subsection evaluates the designed i-PID performance for the closed-loop disturbance-to-position of the laser beam stabilizer. The i-PID is implemented for the laser beam stabilizer platform in closed-loop under active disturbance voltage.

TABLE I
RMS OUTPUT POSITION ERRORS OVER THE TIME INTERVAL $[2 - 25]$ s.

Controller	RMS
PID	0.0226
Robust PID	0.0081
Intelligent PID without MFBM	0.0035

1) *Performances analysis:* The conventional PID controller gains are calculated based on disturbance rejection PID method [1]:

$$K_p = 0.590, \quad K_i = 0.295, \quad K_d = 0.00186. \quad (14)$$

In addition, a Robust PID (RPID) controller which uses a band-pass filter is introduced for a better rejection of the disturbance and improves the stabilization performance.

The next step is to use the proposed i-PID controller that can produce highly competitive solutions for a better disturbance rejection with performance guarantees.

The experimental platform has been used to test the i-PID controller designed previously. The proposed i-PID controller aims at stabilizing the vibrations induced into the beam using the FSM feedback from the position sensor. Due to the sensor noise, a practical PID controller that filters the position signal before taking the derivative has been designed. Figs. 4–6 show the experimental performance of the proposed controllers. Fig. 4 shows the plot of experimental response of the PID controller that is switched from an automated Seeker Mode (SM) to closed-loop after $t = 2$ s. In Fig. 4, the practical PID controller maintains an amplitude of ± 0.06 mm. However this vibration is reduced in Fig. 5 to an amplitude of ± 0.045 mm for the robust PID controller. The response of the intelligent PID controller in Fig. 6 presents a small amplitude of approximately less than ± 0.025 mm. Table I shows that the practical i-PID controller reduces the X-axis output error by more than 50% from the output errors to the robust PID controller and 80% from the output errors of the PID controller. The plots in Fig. 7 show the zoomed view of the two practical controllers over the time interval $[22 - 23]$ s. Fig. 8 shows representative sample trajectories of the laser image on the PSD in the experiment over two different time intervals. Fig. 9 shows the zoomed view of the settling time over the time interval $[2 - 4]$ s. From the obtained practical experimental results, it is clear that the designed i-PID outperforms the practical conventional and robust PID controllers.

2) *Robustness analysis:* To assess the robustness of the control scheme, we performed two different test cases:

- *Disturbance rejection:* Two short terms bounded external disturbance functions are introduced into the closed-loop responses of the system at 10 s and 20 s. Fig. 10, which illustrates responses during the short terms disturbance experiments for PID, RPID and i-PID controllers, demonstrates the ability of i-PID controller to reduce the deviation and brings back the response to set-point in shorter time around $t = 0.2$ s.
- *Robustness with respect to gain variation:* To assess the robustness of the control scheme against model variation,

Fig. 4. Response of real laser beam system with **PID** controller.

Fig. 5. Response of real laser beam system with **Robust PID** controller.

Fig. 6. Response of real laser beam system with **Intelligent PID (i-PID)** controller without MFBM.

Fig. 7. Zoomed views responses: amplitude from [22 – 23] s.

Fig. 8. Screen shots of the laser-beam trajectories on the PSD over two different time intervals: a) **PID** controller vs **PID** controller; b) **Robust PID** controller vs **Robust PID** controller; c) **i-PID** controller vs **i-PID** controller without MFBM.

Fig. 9. Zoomed views responses: settling time from [2 – 4] s.

Fig. 10. Experimental responses of laser beam during two short terms disturbance at time 10 s and 20 s.

uncertainty is introduced on the parameter gain model K . Fig.11 shows the closed loop responses of the system subject to gain variations. We observe that the responses of i-PID controller remain almost constant under gain variations compared to the PID and robust PID controllers. Comparative details are explored in Table II. As it can be observed the RMS of i-PID controller do not change with gain variations from the nominal point whereas PID and RPID controllers vary almost 10% and 5% from their nominal point respectively, which means that the controlled system using i-PID is more robust to gain changes.

TABLE II
RMS OUTPUT POSITION ERRORS: GAIN VARIATIONS OVER THE TIME INTERVAL [2 – 25] s.

Controller	-10%K	K	+7%K
PID	0.0217	0.0226	0.0251
Robust PID	0.0073	0.0081	0.0100
Intelligent PID without MFBM	0.0033	0.0035	0.0036

B. Modulating function-based i-PID controller

Fig. 12 shows the real-time experimental estimation results of the time-varying nonlinear dynamics $F(t)$ and the control

Fig. 11. Experimental responses of the laser-beam trajectories with gain variations: a) PID controller; b) Robust PID (RPID) controller; c) Intelligent PID (i-PID) controller without MFBM.

TABLE III

COMPARATIVE ANALYSIS OF F OVER THE TIME INTERVAL $[5 - 20]$ s.

	Mean	RMS	Variance
$F(t)$ estimated using MFBM	0.0253	0.0488	0.0017
$F(t)$ estimated using SDB	0.0269	0.2462	0.0599

TABLE IV

RMS OUTPUT POSITION ERRORS OVER THE TIME INTERVAL $[5 - 20]$ s.

Controller	RMS
i-PID laser beam response using MFBM	0.0069
i-PID laser beam response using SDB	0.0083

signals input using the MFBM and the SDB. It proves that the estimation of $F(t)$ using the MFBM has small error. Comparative details are explored in Table III.

Fig. 13 shows the real-time experimental laser beam results using MFBM and SDB and Fig. 14 shows representative sample trajectories of the laser image on the PSD in the experiment over two different time intervals using MFBM and SDB. Table IV shows that the real-time i-PID controller using MFBM reduces the axis X output error more than 16% from the output errors to the i-PID controller using SDB. From the obtained results, it is clear that the online designed i-PID controller using MFBM outperforms the designed i-PID controller using SDB and ensures a quite good performance despite the effects of noise. For the time window, generally, it should have enough number of samples (minimum size) to contain information about the system. On the other hand, with a large window the variations of F within the window will be high, and hence the estimation becomes harder. Table V emphasizes this fact by showing simulations for estimating F with respect to different window sizes. It shows the presence of an optimal window size within the range of $[120 - 140]$. However with a large window the estimation failed due the highest value of F that cannot be captured through the PSD.

VI. CONCLUSION

In this paper, an i-PID controller has been designed, implemented and tested to stabilize a laser beam such that the incident laser beam of the FSM is reflected to the center of the position sensor even in the presence of active disturbance and uncertainties. The performance of the presented i-PID controller has been evaluated in closed-loop and has been compared to the conventional PID and robust PID controllers.

Real-time experimental results show that the i-PID controller can achieve better performance results highlighting the effectiveness of the proposed controllers in terms of robustness. In addition, the real-time estimation problem of the unknown function which describes system's uncertainties, modeling errors and disturbances using MFBM has been studied. To conclude, the model-free based control combined with MFBM methods are easy to implement as they do not require an accurate model of the system and have good robustness performance with high position tracking precision. This shows its high potential in the applications.

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Fig. 12. Real-time experimental results: a) $F(t)$ estimated using SDB (blue line) and $F(t)$ estimated using MFBM (red line); b) Control signal using SDB (blue line) and control signal using MFBM (red line).

Fig. 13. Real-time experimental results: Laser beam output response using SDB (blue line) and laser beam output response using MFBM (red line).

Fig. 14. Real-time screen shots performance of the laser-beam trajectories on the PSD over two different time intervals: a) i-PID vs i-PID using SDB; b) i-PID vs i-PID using MFBM; c) i-PID vs i-PID using MFBM (red line) and SDB (blue line).

TABLE V
EFFECT OF THE WINDOW SIZE ON ESTIMATING F .

Number of sample	10	30	60	80	90	100	110	120	130	140
RMS	3.3077	2.4502	1.1298	0.1149	0.0827	0.0774	0.0729	0.0697	0.0610	0.0696
Mean	0.0284	0.0263	0.0257	0.0312	0.0314	0.0308	0.0276	0.0262	0.0255	0.0257
Variance	10.9403	6.0027	1.2759	0.0122	0.0058	0.0050	0.0046	0.0042	0.0031	0.0042

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