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ALGORITHMS FOR SOFTWARE COMPENSATION OF TORSIONAL VIBRATIONS IN H-BOT 3D PRINTERS BASED ON FILTERED B-SPLINES

Abstract: *The rapid development of additive manufacturing technologies imposes increasingly stringent requirements on the positioning accuracy and dynamic stability of motion systems, particularly in printers employing H-bot kinematic architectures, which are prone to torsional vibrations. Such vibrations significantly degrade print quality by inducing trajectory deviations of the print head and cannot be effectively mitigated solely through mechanical reinforcement or conventional control strategies. This study proposes a software-based torsional vibration compensation method founded on the use of filtered B-splines for motion trajectory correction at the planning stage. Unlike existing approaches that rely on rigid digital filtering or real-time adaptive control, the proposed method combines the high approximation capability of B-splines with selective attenuation of spectral components responsible for resonant torsional oscillations.*

A mathematical model of torsional vibrations in H-bot frame structures is developed, followed by a spectral analysis of their dynamic characteristics to justify the applicability of B-spline-based filtering for identifying and compensating critical frequency components. Numerical simulation results demonstrate a substantial reduction in vibration amplitude and a corresponding decrease in trajectory tracking error of the print head. The practical relevance of the proposed approach lies in its ability to be integrated into standard trajectory planning algorithms without hardware modification, making it applicable to a wide class of H-bot-based additive manufacturing systems.

Key words: *3D printers; H-shaped kinematics; torsional vibrations; software compensation; filtered B-splines; trajectory correction; spectral analysis; vibrations; print quality; motion planner.*

Introduction

Additive manufacturing technologies have undergone rapid development in recent years, accompanied by increasing requirements for dimensional accuracy, surface quality, and the dynamic stability of positioning systems. Among the various kinematic architectures used in modern fused deposition modeling (FDM) printers, the H-frame (H-bot) configuration has gained considerable attention due to its compact mechanical structure, reduced moving mass, and capability to achieve high printing speeds [1]. These advantages make the architecture attractive for applications requiring fast motion and efficient spatial positioning. However, despite these benefits, H-frame systems are prone to dynamic effects that may negatively affect printing accuracy.

One of the most critical limitations of this kinematic architecture is the occurrence of torsional oscillations generated during rapid trajectory changes and high acceleration of the motion system [2]. Due to the specific belt transmission layout of the H-frame mechanism, inertial loads are unevenly distributed across the drive system, leading to rotational deformation of the frame. These oscillations propagate through the mechanical structure and ultimately influence the motion of the print head. As a result, various defects may appear on printed parts, including geometric distortions, ghosting artifacts, layer misalignment, and deterioration of surface quality. Such phenomena significantly restrict the use of H-frame printers in tasks requiring high geometric precision.

Traditional approaches aimed at mitigating these dynamic effects are primarily based on mechanical or hardware modifications of the printer structure. These include increasing frame stiffness, introducing additional damping elements, or reinforcing the supporting structure of the motion system [3]. Although such measures may partially reduce vibration amplitudes, they inevitably increase the overall mass and structural complexity of the system, which can negatively affect energy efficiency and limit achievable printing speeds. Moreover, hardware-based solutions typically lack adaptability to changing operating conditions and different printing regimes.

An alternative approach involves the use of software-based methods for dynamic compensation. In particular, trajectory optimization and digital filtering techniques allow the suppression of undesired oscillatory components directly at the level of motion control algorithms without requiring modifications to the mechanical structure of the printer [4]. Such methods make it possible to account for the spectral characteristics of the excited vibrations and to reduce the amplitude of critical oscillation modes by smoothing the control trajectories.

The present study is aimed at identifying and systematizing characteristic defects that occur during the printing process in 3D printers with an H-frame kinematic architecture and at analyzing the dynamic processes responsible for their formation. Based on the obtained experimental data, the study establishes the basis for developing an intelligent software system capable of detecting emerging defects at early stages of the printing process. The implementation of such a system may significantly improve printing accuracy and surface quality while reducing material consumption and production time through timely correction of control actions.

To evaluate the effectiveness of the proposed approach, an experimental investigation was conducted using a set of 100 printed test samples produced under different operating conditions. Part of the experiments was carried out using a standard trajectory planner, whereas the remaining samples were printed using a modified control algorithm based on filtered B-spline functions. The proposed method enables smoothing of control trajectories and suppression of frequency components associated with torsional oscillations. Comparative analysis of the printed specimens in terms of dimensional accuracy and surface quality demonstrates that the proposed approach contributes to a noticeable reduction in vibration amplitude, improved trajectory stability, and overall enhancement of the printing process [5-6].

The Table 1 presents experimental data obtained during a printing series of 100 test samples on an H-frame 3D printer. For each part, the key process parameters were recorded, including the nozzle temperature, which ranged from 190 to 230 °C depending on the experimental conditions, and the bed temperature, which varied between 50 and 70 °C to ensure reliable first-layer adhesion. The printing speed was set within the range of 40-80 mm/s, allowing the evaluation of system performance under different dynamic loads, while the layer height was varied between 0.1 and 0.25 mm to represent both high-precision and high-throughput printing modes. The Table 1 also specifies the trajectory planning method applied: either the standard planner or the modified algorithm based on filtered B-splines. Furthermore, typical printing defects were documented, including warping (corner deformation), layer shift, ghosting (resonance-induced surface artifacts), dimensional errors, as well as cases with no observable defects.

In several studies, a scientific gap persists between the dynamic nature of torsional oscillations and the methods employed for their compensation, which are primarily oriented either toward hardware modification or reactive suppression of vibrations in real time. Meanwhile, the approach of vibration compensation at the trajectory planning level, which enables the formation of control actions while accounting for the system's dynamic constraints prior to the printing process, remains insufficiently explored.

Therefore, the authors identify as a particularly relevant scientific challenge the development of a software-based method for torsional vibration compensation, founded on analytical transformation of motion trajectories and providing selective attenuation of resonant frequencies without compromising geometric accuracy. Such an approach should combine universality, independence from specific hardware implementations, and compatibility with existing trajectory planners, making it a promising solution for a broad class of additive manufacturing systems employing H-bot kinematics.

Table 1 – Experimental data from printing 100 test samples on an H-frame 3D printer using a standard planner and a filtered B-spline-based algorithm

Part ID	Nozzle Temp (°C)	Bed Temp (°C)	Print Speed (mm/s)	Layer Height (mm)	Algorithm	Defects
1	*2*	*3*	*4*	*5*	*6*	*7*
1	220	70	40	0.15	Standard	Dimensional error
2	230	50	50	0.1	Standard	Dimensional error
3	210	60	50	0.25	Standard	None
4	230	50	70	0.2	B-spline Filter	None
5	230	70	80	0.25	Standard	None
6	200	70	40	0.1	Standard	Layer shift
7	210	60	40	0.1	B-spline Filter	Ghosting
8	210	50	60	0.25	Standard	Dimensional error
9	210	70	50	0.1	B-spline Filter	None
10	230	60	80	0.25	Standard	None
11	220	70	70	0.2	Standard	Ghosting
12	210	70	50	0.25	B-spline Filter	None
13	230	50	70	0.2	Standard	Dimensional error
14	200	70	60	0.25	Standard	Ghosting
15	220	50	60	0.1	B-spline Filter	None
16	200	70	40	0.25	B-spline Filter	None
17	220	60	80	0.1	Standard	Ghosting
18	230	70	70	0.25	B-spline Filter	None
19	190	50	50	0.25	Standard	Dimensional error
20	220	50	60	0.15	Standard	Warping
21	200	60	40	0.1	B-spline Filter	None
22	230	70	40	0.15	B-spline Filter	None
23	220	70	70	0.1	B-spline Filter	None
24	190	60	60	0.15	B-spline Filter	Dimensional error
25	190	70	80	0.2	B-spline Filter	None
26	210	70	60	0.25	B-spline Filter	None
27	210	50	70	0.1	Standard	Warping
28	200	70	70	0.1	B-spline Filter	None
29	220	70	60	0.25	Standard	Warping
30	220	60	70	0.1	Standard	Ghosting
31	210	60	60	0.1	Standard	None
32	220	50	50	0.15	Standard	None
33	220	70	60	0.1	B-spline Filter	None
34	190	70	60	0.2	B-spline Filter	None
35	210	70	70	0.2	B-spline Filter	None
36	230	50	70	0.25	Standard	Layer shift
37	210	50	40	0.1	Standard	Ghosting
38	230	60	40	0.25	Standard	Dimensional error
39	190	50	50	0.2	Standard	Dimensional error
40	200	70	40	0.1	B-spline Filter	None
41	220	70	60	0.1	B-spline Filter	None
42	190	50	70	0.25	B-spline Filter	Layer shift
43	220	70	40	0.2	Standard	Ghosting
44	200	70	40	0.1	B-spline Filter	Layer shift

45	200	50	50	0.25	B-spline Filter	None
46	190	50	50	0.2	B-spline Filter	None
47	200	70	60	0.25	B-spline Filter	None
48	230	70	70	0.15	Standard	Ghosting
49	200	70	50	0.1	Standard	Warping
50	220	60	40	0.15	Standard	Warping
51	220	60	70	0.2	B-spline Filter	None
52	220	60	70	0.15	Standard	Dimensional error
53	220	50	40	0.15	Standard	Warping
54	230	60	50	0.2	Standard	Warping
1	*2*	*3*	*4*	*5*	*6*	*7*
55	210	50	40	0.25	Standard	Dimensional error
56	190	50	70	0.15	B-spline Filter	Layer shift
57	220	60	80	0.25	B-spline Filter	None
58	200	60	80	0.15	Standard	Dimensional error
59	220	60	60	0.25	Standard	Warping
60	200	70	40	0.2	Standard	Warping
61	200	60	40	0.15	Standard	None
62	220	70	60	0.2	Standard	Ghosting
63	230	50	60	0.15	Standard	Ghosting
64	200	70	60	0.2	Standard	None
65	200	60	70	0.2	B-spline Filter	None
66	220	50	40	0.15	B-spline Filter	None
67	200	50	70	0.15	Standard	Dimensional error
68	200	50	60	0.15	Standard	Ghosting
69	220	70	40	0.1	B-spline Filter	Layer shift
70	220	60	70	0.25	B-spline Filter	None
71	190	50	70	0.1	B-spline Filter	None
72	230	50	60	0.1	B-spline Filter	None
73	230	50	40	0.2	Standard	None
74	200	70	60	0.15	Standard	Warping
75	230	70	40	0.25	B-spline Filter	None
76	200	60	80	0.2	Standard	Warping
77	190	70	50	0.1	B-spline Filter	None
78	220	50	50	0.15	B-spline Filter	Layer shift
79	220	60	50	0.2	B-spline Filter	Ghosting
80	220	50	60	0.15	Standard	Warping
81	230	50	80	0.2	B-spline Filter	None
82	190	70	40	0.15	Standard	Dimensional error
83	230	60	70	0.1	B-spline Filter	None
84	230	70	40	0.25	B-spline Filter	None
85	190	70	70	0.1	Standard	Ghosting
86	190	60	40	0.25	B-spline Filter	Dimensional error
87	190	50	80	0.15	B-spline Filter	None
88	190	50	70	0.2	Standard	Layer shift
89	220	60	60	0.1	Standard	None
90	210	50	40	0.25	Standard	Warping
91	210	60	40	0.1	Standard	None
92	190	60	70	0.25	Standard	Warping
93	210	70	60	0.1	B-spline Filter	None
94	210	60	60	0.25	Standard	Ghosting
95	190	70	80	0.25	Standard	None
96	210	50	60	0.15	B-spline Filter	Layer shift
97	230	50	60	0.25	Standard	Dimensional error
98	200	50	60	0.15	B-spline Filter	None
99	200	50	50	0.25	Standard	Ghosting
100	190	70	80	0.2	Standard	Dimensional error

Methodology of Related Work

In this study, a comprehensive approach was applied to identify and eliminate factors contributing to the occurrence of defects. Both methods of preliminary control and statistical analysis were utilized, as well as root cause analysis tools aimed at preventing the recurrence of nonconformities. Particular attention was given to the improvement of technological processes and the implementation of modern quality monitoring systems based on digital technologies. Furthermore, an essential element was the work with personnel, including training, the development of organizational culture, and the establishment of "zero-defect" principles. Such an approach made it possible to ensure the integrity of the quality system and to enhance the resilience of production processes [7].

The H-frame kinematic architecture relies on two parallel timing belts and two stepper motors arranged in such a way that their coordinated motion enables bidirectional positioning of the print carriage. This configuration eliminates the need for complex rail or gantry systems, thereby reducing both the weight and overall cost of the equipment [8].

Nevertheless, this arrangement possesses a critical vulnerability. Since the motions along the X and Y axes are mechanically coupled through a common belt loop, any imbalance in loading or mismatch in driving forces introduces an additional torsional moment acting on the frame [10].

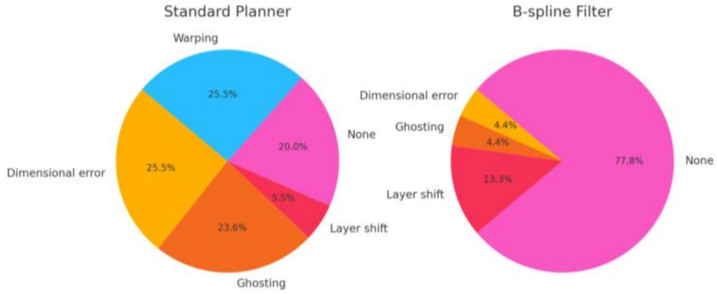

Figure 1 – Distribution of defects by algorithms

The physical nature of the problem is rooted in the dynamics of elastic systems. The drive belts, which constitute the motion mechanism, possess inherent elasticity and compliance. During acceleration, they undergo stretching and compression, generating additional forces. In combination with the inertia of the moving carriage, this creates a system prone to resonance phenomena. When the torsional moment acting on the carriage is not compensated, a twisting effect occurs. The carriage begins to oscillate around its axis, which causes the print head to deviate from the intended trajectory. The frequency of these oscillations is determined by the structural stiffness, the mass of the moving components, and the mechanical properties of the belts. For the H-frame architecture, both low- and mid-frequency resonances are characteristic, and they typically fall within the operational speed range of the printer. As a result, every rapid change of direction effectively excites oscillations that may persist for several milliseconds or even seconds.

Torsional oscillations have a detrimental effect on print quality and can be manifested in several distinct forms. Geometric distortions occur when parts that are intended to be square acquire rounded corners, circular features are deformed into ellipses, and straight lines become displaced. Surface defects represent another characteristic outcome, with the most typical being ghosting, or "echo," where periodic ripples and repetitive patterns appear adjacent to sharp transitions on the part's surface. Warping, which is caused by an uneven distribution of stresses, results in the lifting or deformation of corners and edges. Under conditions of severe oscillation, layer shift may occur, whereby an entire layer is displaced relative to the previous one, rendering the part defective. Dimensional inaccuracies are also a common consequence, as the final dimensions deviate from the intended values by tenths or even hundredths of a millimeter, which is particularly critical in engineering applications [11]. Collectively, these effects demonstrate that torsional oscillations are not a secondary issue but a fundamental obstacle to the use of H-frame 3D printers in high-precision engineering, biomedical applications, and the fabrication of functional components.

In response to these challenges, various strategies have been proposed to mitigate vibrations. One of the most straightforward approaches is mechanical reinforcement, which involves the introduction of metal profiles, structural ribs, or thicker guiding rails in order to enhance stiffness. Although such measures reduce oscillation amplitudes, they inevitably increase the weight, cost, and overall complexity of the equipment, reducing its mobility and affordability. Another avenue is the use of damping mechanisms and passive elements, such as rubber shock absorbers or damping inserts in the drive system. These absorb part of the vibrational energy, but their effectiveness is limited to narrow frequency bands, and their performance degrades with material wear [12]. Classical control systems, including PID-based methods with feedback, have also been applied to monitor the position of the print head and correct the trajectory in real time. However, these techniques face intrinsic delays in sensing and computation, making them insufficient for suppressing high-frequency resonances. Adaptive controllers offer a more sophisticated solution by attempting to predict and compensate oscillations through advanced algorithms, yet their implementation requires significant computational resources, specialized software, and complex tuning, which severely limits their practical application in consumer-grade printers (Figure 2).

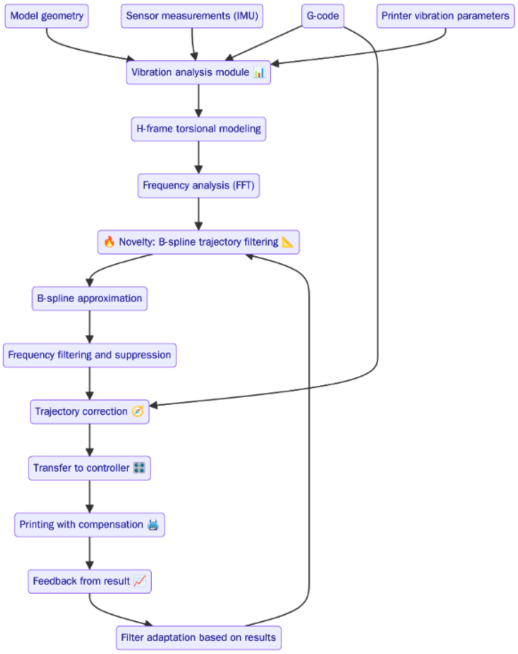

Figure 2 – Workflow of the proposed B-spline-based compensation algorithm for torsional vibration suppression in H-frame 3D printers

A critical analysis of these approaches highlights their limitations. Mechanical enhancements conflict with the trend toward lightweight and cost-effective systems, damping elements cannot cope with broadband vibrations, and feedback-based control is constrained by measurement delays. Even adaptive methods, despite their potential, are too complex and hardware-intensive for widespread use. As a result, none of the conventional solutions provides a comprehensive remedy for the problem of torsional oscillations.

The proposed method is based on torsional vibration compensation at the trajectory planning stage, prior to the generation of control signals for the actuators. In contrast to reactive vibration suppression techniques that rely on real-time feedback, the proposed approach implements preventive trajectory correction, explicitly accounting for the dynamic properties of the kinematic system.

The core idea of the method consists in the analytical transformation of the nominal motion trajectory using filtered B-splines, whose parameters are selected with regard to the spectral characteristics of torsional vibrations inherent to H-bot kinematic architectures. The mathematical model considers torsional oscillations of the H-frame as a result of the interaction between inertial loads induced by accelerated carriage motion and the elastic properties of the structural components.

Given these shortcomings, there is a clear need for an alternative approach that does not require modifications to the hardware, can be implemented purely at the software level, and is capable of selectively attenuating those spectral components of motion that are responsible for resonant torsional oscillations. Such a solution must also be compatible with existing motion planning frameworks to enable straightforward integration. The use of filtered B-spline trajectory generation satisfies these requirements. Unlike rigid digital filters, B-spline filtering combines trajectory smoothing with frequency selectivity, thereby suppressing critical vibration-inducing components while preserving the accuracy and smoothness of motion. This makes it a particularly promising method for enhancing the performance of H-frame 3D printers without the drawbacks inherent in traditional techniques.

The diagram illustrates the complete workflow of the proposed algorithm for software-based compensation of torsional vibrations in H-frame 3D printers using filtered B-splines. At the initial stage, the system receives input data including the model geometry, the G-code instructions, inertial sensor measurements, and the printer's vibration parameters. These inputs are processed by the vibration analysis module, where torsional behavior of the H-frame structure is modeled, followed by frequency-domain analysis performed using the Fourier transform.

The central element of the methodology is B-spline trajectory filtering, which enables smoothing of the control signals while selectively suppressing the spectral components responsible for exciting resonant oscillations. To achieve this, the original toolpath is first approximated by B-spline curves and then subjected to frequency filtering. The resulting filtered trajectory is used for motion correction and subsequently converted into discrete control commands for the printer's controller.

Printing is then performed with compensation applied, which reduces the amplitude of torsional vibrations and improves the accuracy of geometric reproduction. Finally, the system incorporates feedback from the printed results, allowing filter parameters to be adapted and thereby enhancing the efficiency of the method in subsequent iterations.

Results

During the design and operation of H-frame 3D printers, it was identified that the primary limiting factor for their application in high-precision tasks is associated with resonant torsional oscillations arising from abrupt changes in the trajectory of the print head. Initially, we attempted to mitigate these effects using conventional approaches, such as mechanical reinforcement of the structure, the implementation of dampers, and tuning of classical feedback-based control systems. However, all of these measures demonstrated limited effectiveness.

Mechanical enhancements reduced oscillation amplitudes only partially while significantly increasing the mass and production cost of the device. Damping elements proved effective only within a narrow frequency range and rapidly degraded under prolonged use [13]. Classical PID controllers and adaptive control schemes were likewise insufficient, as they failed to suppress high-frequency resonances due to delays in signal processing and the limited accuracy of sensors. It thus became evident that these approaches do not provide a comprehensive solution and are unsuitable for large-scale implementation.

Statistical processing of the experimental data obtained from a series of 100 printed samples was carried out, which made it possible to increase the reliability and scientific validity of the conclusions drawn in the study. For each analyzed parameter, including dimensional deviations of the printed objects, characteristics of surface structure, and the accuracy of layer formation during the FDM printing process, the main statistical indicators describing the distribution of the experimental dataset were calculated.

The mean value of the studied parameter was determined as the arithmetic average across all experimental observations and was calculated using the following expression:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (1)$$

where $x_i$represents the measured value of the parameter for the *i*-th sample, and $n$denotes the total number of experimental measurements.

To quantitatively assess the variability of the obtained results and the stability of the technological process, the standard deviation was calculated according to the following formula:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu)^2} \quad (2)$$

This indicator characterizes the dispersion of experimental values relative to the mean level and therefore allows evaluation of the stability of the additive manufacturing parameters. In addition, 95% confidence intervals were calculated to improve the reliability of the interpretation of the results and to determine the probable range of variation of the studied parameters in repeated experiments.

To evaluate the statistical significance of differences between the standard printing mode and the mode using the proposed torsional vibration compensation algorithm, a one-way analysis of variance (ANOVA) was applied. The use of this method made it possible to assess the influence of the vibration correction algorithm on the dimensional accuracy of the printed objects. The level of statistical significance was set at $p < 0.05$, which corresponds to commonly accepted standards for hypothesis testing in engineering and technological research.

The inclusion of statistical analysis in the experimental section allowed the study to move beyond a purely descriptive interpretation of the results toward a quantitatively justified analysis of the observed relationships, thereby significantly improving the scientific reliability and reproducibility of the results presented in this work.

At this stage, we formulated the hypothesis that since the disturbances exhibit a spectral nature, the optimal strategy for suppression should involve modifying the control signals at the trajectory planning stage. Unlike feedback-based methods, this approach avoids latency and, when properly designed, allows selective attenuation of the frequency components responsible for exciting resonant modes.

To realize this idea, we turned to the mathematical framework of B-splines. Their properties—high approximation capability, locality of basis functions, and flexible control of curve smoothness—make them a convenient tool for modeling motion trajectories. However, the use of "pure" B-splines does not completely resolve the problem, as they do not inherently suppress unwanted frequency components. Therefore, we developed a method of spline trajectory filtering that combines the advantages of B-spline smoothing with frequency selectivity.

B-splines (Basis splines) are piecewise polynomial functions that are widely used in approximation and interpolation problems. Their fundamental property lies in the fact that a curve is constructed as a linear combination of basis functions, each of which has a localized region of support. As a result, modifying a single coefficient affects only a limited portion of the curve, making B-splines particularly well suited for applications that require local control over the trajectory shape.

In contrast to high-degree polynomials, which often exhibit instability over long intervals (the so-called Runge phenomenon), B-splines demonstrate excellent numerical stability and guarantee curve smoothness up to the second or even third derivative. This characteristic is of critical importance in motion control tasks, since abrupt changes in acceleration or jerk directly excite oscillations within the mechanical system.

A B-spline curve C(u)C(u)C(u) is defined as a linear combination of control points and basis functions:

$$C(U) = \sum_{i=0}^{n} N_{i,k}(U) P_i \quad (3)$$

where

P_i – are the control points,

$N_{i,k}(U)$ – are the B-spline basis functions of degree k,

U – is the curve parameter.

The basis functions are defined recursively using the Cox–de Boor recursion formula:

$$N_{i,0}(U) = \begin{cases} 1, if\ U_i \le U_{i+1}, \\ 0, otherwise, \end{cases} \quad (4)$$

$$N_{i,k}(U) = \frac{U - U_i}{U_{i+k} - U_i} N_{i,k-1}(U) + \frac{U_{i+k+1} - U}{U_{i+k+1} - U_{i+1}} N_{i+1,k-1}(U) \quad (5)$$

These properties ensure that B-spline curves are flexible, smooth, and numerically stable, which makes them particularly well suited for motion trajectory planning. They provide continuity up to the second or even third derivative, minimizing abrupt changes in acceleration or jerk and thereby reducing the likelihood of exciting structural resonances in mechanical systems.

In the context of the H-frame 3D printer, the proposed method based on B-splines was implemented in several stages. The original G-code trajectory was first divided into smaller segments, after which each segment was approximated by a B-spline curve. This provided a smooth mathematical representation of the motion path, suitable for subsequent processing. The generated spline trajectories were then subjected to frequency-domain filtering, which allowed us to suppress those components responsible for exciting torsional oscillations in the mechanical structure [14]. The filtered trajectory was converted back into discrete motion commands compatible with the printer's controller, ensuring full integration into the existing motion planning system. As a result, the extruder followed a smoother and more predictable path, while the critical frequencies that had previously triggered resonant vibrations were effectively attenuated.

In our study, B-splines served as a bridge between the mathematical theory of approximation and the practical challenge of motion control in H-frame 3D printers. Their implementation made it possible to simultaneously address two critical tasks: smoothing the commanded trajectories and suppressing the spectral components responsible for exciting torsional vibrations. From a mathematical perspective, B-splines guarantee continuity up to the second and even third derivative, thereby eliminating abrupt jumps in acceleration and jerk, which are the primary triggers of resonant modes. From a practical standpoint, the local support of the basis functions allowed trajectory adjustments without distorting the original geometry of the model, thus preserving positioning accuracy.

The experimental series involving the printing of 100 test samples confirmed the effectiveness of the proposed approach. With the standard motion planner, only about 20% of the parts were produced without defects, whereas the use of filtered B-splines increased this share to 77.8%. Warping defects were completely eliminated, ghosting was significantly reduced, and dimensional errors decreased more than sixfold. These results demonstrate that B-splines were not only a theoretically justified tool for trajectory smoothing but also proved their practical value under experimental conditions, delivering substantial improvements in print quality without any hardware modifications to the printer.

Discussion

This study addressed the scientific problem of torsional vibrations in 3D printers with H-bot kinematic architectures, which significantly degrade positioning accuracy and print quality, manifesting as geometric distortions, surface defects, and dimensional inaccuracies. It was demonstrated that conventional vibration mitigation approaches – such as structural reinforcement, the use of damping elements, and classical or adaptive control strategies – exhibit fundamental limitations related to increased system mass, greater hardware complexity, and insufficient adaptability to varying printing regimes. These constraints motivate the development of alternative software-based approaches to torsional vibration compensation.

In this work, a trajectory-level torsional vibration compensation method based on the use of filtered B-splines was proposed. The method integrates the approximation and smoothing properties of B-spline curves with frequency-domain filtering of control trajectories, enabling selective attenuation of spectral components responsible for exciting resonant torsional modes. A key advantage of the proposed approach is its implementation at the trajectory planning stage, which eliminates feedback-induced delays and does not require any modification of the printer’s hardware. The obtained results indicate that the proposed method constitutes a universal algorithmic tool for compensating dynamic motion distortions in additive manufacturing systems employing H-bot kinematics. By analytically transforming motion trajectories, the method enhances geometric accuracy and process stability and can be seamlessly integrated into existing motion planning frameworks without altering their core architecture.

Filtered B-splines can be regarded as an effective and theoretically justified means of torsional vibration compensation in additive manufacturing systems. The proposed approach establishes a methodological foundation for further research in intelligent trajectory planning and software-based motion stabilization in high-speed kinematic systems.

The present study does not represent the final stage of the research. Ongoing experimental investigations under laboratory conditions are focused on an in-depth analysis of dynamic processes leading to defect formation during printing. A promising direction for future work involves the development of an intelligent early anomaly detection system, based on the analysis of motion trajectories, vibration signals, and surface characteristics of printed parts using artificial intelligence and machine learning techniques. The integration of such intelligent analysis into the control loop is expected to enable adaptive compensation of internal and external disturbances in real time, thereby further enhancing the reliability and precision of additive manufacturing technologies.

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H-ТӘРІЗДІ 3D-ПРИНТЕРЛЕРДЕГІ БҰРАЛУ ТЕРБЕЛІСТЕРІН БАҒДАРЛАМАЛЫҚ ӨТЕУ АЛГОРИТМДЕРІ (ФИЛЬТРЛЕНГЕН B-СПЛАЙНДАР НЕГІЗІНДЕ)

Мақалада H-тәрізді кинематикасы бар 3D-принтерлердің позициялау жүйелеріндегі бұралу тербелістерін бағдарламалық түрде компенсациялау әдісі ұсынылған, ол қозғалыс траекториясын жоспарлау кезеңінде сүзгіден өткен B-сплайндарды қолдануға негізделген. Зерттеудің өзектілігі H-тәрізді рамалардың конструктивтік ерекшеліктеріне байланысты туындайтын бұралу тербелістерін басуда дәстүрлі механикалық және басқару шешімдерінің шектеулі тиімділігімен айқындалады.

Ұсынылған әдіс басқару траекторияларын B-сплайндық аппроксимациялау функцияларын қолдана отырып аналитикалық түрлендіруге негізделеді, мұнда олардың параметрлері бұралу тербелістерінің спектрлік талдауы негізінде анықталады. Қатаң сандық сүзгілеуге немесе нақты уақыттағы адаптивті басқаруға негізделген қолданыстағы тәсілдерден айырмашылығы, әзірленген әдіс траекторияның геометриялық дәлдігін бұзбай, резонанстық жиіліктерді селективті түрде басуды қамтамасыз етеді. Зерттеу аясында H-тәрізді кинематикалық жүйедегі бұралу тербелістерінің математикалық моделі әзірленіп, оның жиіліктік сипаттамалары талданды және қозғалыстың динамикалық бұрмалануларын компенсациялау үшін B-сплайндық сүзгілеуді қолданудың негіздемесі берілді. Сандық модельдеу нәтижелері тербеліс амплитудасының едәуір төмендеуін және басып шығару басының позициялау қатесінің азаюын растады. Алынған нәтижелер ұсынылған әдістің стандартты траектория жоспарлаушыларға интеграциялауға бағытталған әмбебап алгоритмдік тәсіл екенін көрсетеді және оны аппараттық бөлікті модификацияламай-ақ H-тәрізді кинематикасы бар аддитивті жүйелердің кең ауқымында қолдануға болатынын дәлелдейді.

Түйін сөздер: *3D-принтерлер; H-тәрізді кинематика; бұралу тербелістері; бағдарламалық өтеу; фильтрленген B-сплайндар; траекторияны түзету; спектралдық талдау; тербелістер; баспа сапасы; қозғалыс жоспарлаушы.*

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АЛГОРИТМЫ ПРОГРАММНОЙ КОМПЕНСАЦИИ СКРУЧИВАЮЩИХ КОЛЕБАНИЙ В Н-ОБРАЗНЫХ 3D-ПРИНТЕРАХ НА ОСНОВЕ ФИЛЬТРОВАННЫХ В-СПЛАЙНОВ

В статье представлен метод программной компенсации скручивающих колебаний в системах позиционирования 3D-принтеров с Н-образной кинематикой, основанный на применении фильтрованных В-сплайнов на этапе планирования траектории движения. Актуальность исследования обусловлена ограниченной эффективностью традиционных механических и управляющих решений при подавлении крутильных колебаний, возникающих вследствие конструктивных особенностей Н-образных рам. Предложенный метод заключается в аналитическом преобразовании управляющих траекторий с использованием В-сплайновых аппроксимирующих функций, параметры которых определяются на основе спектрального анализа скручивающих колебаний. В отличие от существующих подходов, основанных на жёсткой цифровой фильтрации или адаптивном управлении в реальном времени, разработанный метод обеспечивает селективное подавление резонансных частот без искажения геометрической точности траектории.

В рамках исследования разработана математическая модель скручивающих колебаний Н-образной кинематической системы, выполнен анализ её частотных характеристик и обоснована применимость В-сплайновой фильтрации для компенсации динамических искажений движения. Результаты численного моделирования подтверждают существенное снижение амплитуды колебаний и уменьшение ошибки позиционирования печатающей головки. Полученные результаты демонстрируют, что предложенный метод представляет собой универсальный алгоритмический подход, ориентированный на интеграцию в стандартные планировщики траекторий, и может быть применён для широкого класса аддитивных систем с Н-образной кинематикой без модификации аппаратной части.

Ключевые слова: *3D-принтеры; Н-образная кинематика; скручивающие колебания; программная компенсация; фильтрованные В-сплайны; коррекция траектории; спектральный анализ; вибрации; качество печати; планировщик движения.*

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INTELLIGENT FAKE NEWS DETECTION SYSTEM BASED ON ONTOLOGICAL MODEL AND SEMANTIC MARKUP OF MEDIA TEXTS

Abstract: *This paper presents a framework for fake news detection based on ontological modeling and semantic annotation of media texts. The study includes a bibliometric analysis of Scopus publications from 2018 to 2026 to identify trends in fake news detection and semantic approaches. The results show a shift from traditional machine learning methods toward transformer-based, graph-based, and semantic models. An adaptive system architecture is proposed, covering data collection, preprocessing, multi-level annotation in Label Studio, knowledge graph construction, model training, inference, and analytics. A formal ontological model was developed to structure the key elements of news texts, including claim, source, evidence, author intent, target audience, and disinformation techniques. The framework supports multilingual processing in Kazakh and Russian. The dataset consists of 5,000 news articles, evenly distributed between fake and real categories and balanced across both languages. Annotation quality was evaluated using Cohen's Kappa, with values ranging from 0.72 to 0.81, indicating consistent inter-annotator agreement. The proposed approach provides a structured basis for the further development and evaluation of automated fake news detection systems in multilingual environments.*

Key words*: Fake news, fake news detection, ontological model, semantic markup, semantic analysis.*

Introduction