ON NONLINEARITY CONTROL OF CNC FEED DRIVES

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ABSTRACT

A Unified Reconfigurable Open Control Architecture (UROCA) aims at unifying the reconfiguration aspects and managing the interaction amongst the different operating levels of individual machining control systems that are likely to perform in reconfigurable manufacturing systems. The hierarchical control structure of UROCA demands the usage of a supervisory control scheme in order to manage operations of supervisory and servo controllers altogether into a reconfigurable control process. The main function of the supervisory unit is to serve as a switching/reconfiguring logic amongst different available controllers, according to need, in order to maintain motion output within the permitted limits. Due to backlash, efficiency of machine tools will be undesirably turned down causing higher vibrations, lower contouring accuracy, and may draw the whole system into instability region. A Switching control scheme designated to manage the control process where two different controllers with two different control functionalities, acting differently in two vital zones – one of them where the backlash lies, and the other when moving past the backlash – is the main topic of this paper. The proposed switching schemes emphasize a reconfiguration aspect on the control process level for machine tools as perceived, investigated and resolved by the physical and control layers located at the deliberative part of the UROCA architecture.

SUR LE CONTROLE NON-LINEAIRE DE CNC 'FEED DRIVES'

RÉSUMÉ

Une Architecture Unifiée de Contrôle d'Ouverture de Reconfigurable (UROCA) a pour desseins l'unification des aspects de reconfiguration et gérer l'interaction parmi les niveaux d'opérations différents de systèmes de contrôle d'ajustage individuels qui vont en toute probabilité exécuter dans les systèmes reconfigurable industriels. La structure hiérarchique de contrôle de UROCA exige que l'usage d'un arrangement de contrôle de supervision afin de gérer des opérations de contrôleurs de supervision et servo entièrement dans un procédé de contrôle de reconfigurable. La fonction principale de l'unité de supervision sera obligée à servir d'une logique de commutation modifiant la composition d'un ordinateur parmi les contrôleurs disponibles différents, selon le besoin, afin de maintenir la production de mouvement dans les limites permises. La réaction violente (backlash) change l'efficacité des machine d'outils, causant indésirablement de plus hautes vibrations, et abaisse la précision de contouring, et peut dessiner le système entier dans la région d'instabilité. Un arrangement de contrôle de Commutation a désigné pour gérer le procédé de contrôle où deux contrôleurs différents avec deux caractères fonctionnel de contrôle différents, agissant différemment dans deux zones vitales – un d'eux où la réaction violente couche, et l'autre en déplacant le passé la réaction violente – est le sujet principal de ce papier. Les arrangements différents de commutation ont été formulés souligne un aspect de reconfiguration sur le niveau de procédé de contrôle pour les machine outils comme perçu, examiné et résolu par les couches physique et de contrôle a localisé à la partie mûrement réfléchie de l'architecture de UROCA.

INTRODUCTION

Computer numerical control (CNC) machine tools as well as Computer-aided manufacturing (CAM) systems are invading every single corner in today's manufacturing industries. To machine a desired part, a CAM system generates the required tool path for the CNC machine tool so that it can cut the surfaces of the part. On the other hand, a CAD/CAM integration considers the achievement of automatic production process from the design specifications – well represented by a CAD model – to a final product. Accordingly, the scope of motion controls of CNC machine tools covers three areas as depicted in Fig. 1 (Altintas, [1], Chou and Yang [2,3], and Koren, [3]):

1. CAD model to cutter path conversion; involves feature recognition, geometry intersection, offsetting, etc.
2. Cutter path to motion trajectory conversion; referred also as command generation and it includes kinematics of coordinated motion, machine dynamics, and interpolators design.
3. Motion trajectory realization that involves control design.

As time goes on, product model lifetimes are decreasing and customer demands are constantly changing. In order for industries to survive in today's competitive market, their manufacturing systems must be able to respond effectively to these ongoing changes. With such a rapidly changing manufacturing environment, the need for Reconfigurable Manufacturing Systems is immense. A Reconfigurable Manufacturing System is one designed at the advent for rapid change in its structure, as well as its hardware and software components in order to accommodate rapid adjustment of production capacity needed in response to new market circumstances, and functionality needed to produce a new part or overcome an emergent event (Koren *et al.* [5]). An RMS has various distinct characteristics including: modularity, integrability, customizability, and diagnosability. Machine tools are almost the main player on the physical level for a modern manufacturing system where reconfigurability shall be introduced. Aspects of reconfiguration for machine tools can be seen from 5 interrelated levels: system, software, control, machine, and process levels. Technological impacts and variance among developed systems rely on the control level, *see* Fig. 2, as an intermediate environment; where receiving information from the physical/machine level and delivering to the system level components (Mehrabi *et al.* [6]). We are concerned about the control level in this study, by which it is directly connected to a physical cause – backlash in our case.

Since there is variety of control architectures that engulf the hardware and software components/objects, they also differ to a high extent in concept and infrastructure due to the dissimilitude in applications, from which was the motivation for UROCA project to launch. Unified reconfigurable open control architecture (UROCA) is a research project, which aims at unifying the reconfiguration aspects and managing the interaction of individual machining control systems which perform in a reconfigurable manufacturing system. Instead of dealing with closed proprietary control environment, open software/hardware technology will be significantly supporting the coming RMS operations. UROCA targets at the development of an intelligent control architecture that supports multi-vendor, plug-and-play, modular criteria for machine tools as well as stationary and mobile robotic systems (ElBeheiry *et al.*, [7]).

The existence of external disturbances, measurements inaccuracies, load variation, effects of inertia and flexibility and parasitic effects – such as backlash, friction, etc. – call for the use of intelligence and adaptability obtained by reconfigurable control systems. This would limit the use of the regular PID controllers, which prevails in the world of CNC machine tools, giving valuable opportunity for other types of controllers to be implemented. Supervisory control has proven solid grounds at achieving foreseen goals of intelligence and adaptability, especially when switching from one controller to another according to the current need. Supervisory control concept also supports the structure of hierarchical control as a mediator between the physical level and the more intelligent layers atop. According to ElBeheiry *et al.* [7], supervision is of three types: pre-routed, estimator-based and performance-based supervision. The last one has been chosen in our study since it provides good data inputs for system diagnosis and state estimation whenever needed for the operation of advanced controllers. Multiple controllers are available for the supervisor to switch over depending on the functionality needed. These controllers are designed based upon different dynamic models which necessarily vary according to predetermined operating conditions.

As we mentioned before, backlash in this study has been considered as the only physical cause for reconfiguration at the control level. Backlash was coined around 1815, and is a compound word denoting a backward lash (violent movement or reaction). In technical circles this has come to mean "the play between adjacent moveable parts (as in a series of gears)," or "the jar caused by this when the parts are put into action" as introduced by McKechnie [8]. Recently, a state-of-the-art controls perspective was published in book form by two main researchers in this field Tao and Kokotović [9]. This work is based on numerous articles and proceedings of theirs over the past decade or so; a huge number of which were printed in a small concentration of journals in the period 1993-1995 alone [9-11].

After pointing out the introductory basics beyond the area of this research topic, we investigate the modeling aspects of machine tool feed drive systems as well as backlash modeling in Section two. In Section three, control strategies are introduced for backlash compensation. In Section four, supervisory control concepts are discussed. In Section five, simulation results are shown for feed drive systems with and without backlash as well as switching control strategies compared with the standard backlash compensation method. Finally, we conclude our study in Section six.

MODELING MACHINE TOOL FEED DRIVES WITH BACKLASH

Machine tool feed drives control the positions and velocities of machine tool slides or axes in accordance with commands referenced by CNC interpolator. Due to the inertia, stiffness and damping of the different components of feed drive systems, the feed drive maximum delivered torque should be sufficient to undergo an acceptable cutting operation. An example of a feed drive for a CNC machine tool is shown in Fig. 3.

Although machine tool designs vary immensely, the mechanical configurations of feed drive systems are largely standardized. In almost all cases, the recirculating ball screw has established itself as the solution for converting the rotary motion of the servomotor into linear slide motion. The servomotor and ball screw drive are usually directly coupled. Accurate modeling and identification of feed drive dynamics is a paramount stage in formulating a high performance CNC machine tool control. Feed drive components cannot be dealt with as a complete rigid body, yet full elasticity represented by FEA methods could be obscenely time-consuming, especially, in a real time environment such that of controllers. Models of machine tool feed drive systems are of various natures depending on the number of degrees of freedom considered. Most traditional machine tool controllers are of the closed loop type where feedback signal is taken from the motor side (Altintas [1], Koren [4], and Renton and ElBestawi [12]). The plant model is usually of two-degrees-of-freedom nature (Matsubara *et al.* [13]).

The most widely-used model used to interpret the backlash is called the dead zone model. It incorporates backlash within a 2-inertia system, and also considers the simplest form that embodies that intrinsic problem. We are using the two-inertia system with backlash and stiffness which can be described as following:

$$J_m\ddot{\theta}_m + c_m\dot{\theta}_m = u - \vartheta \tag{1}$$

$$J_l\ddot{\theta}_l + c_l\dot{\theta}_l = \vartheta \tag{2}$$

Where the subscripts m and l stand for motor side and load side, respectively, $u(t)$ is the control input, ϑ is the spring force between the two masses. For convenience, the mathematical model of the feed drive is put down in terms of torsional inertia and stiffness. i.e., the translational movement of the table is transformed into an equivalent rotary movement, and due to which the mass of the table is converted into an equivalent inertia. The spring force ϑ is a function of the motor position, $\theta_m(t)$, the load position, $\theta_l(t)$, and backlash, $\delta(\theta_d)$, such that:

$$\vartheta = k_s\delta(\theta_d) \tag{3}$$

Where $k \geq 0$, is the spring stiffness, and $\delta(\theta_d)$ is a dead-zone characteristic used to model the backlash effect:

$$\delta(\theta_d) = \begin{cases} (\theta_d - \beta) & \theta_d > \beta, \\ 0 & |\theta_d| < \beta, \\ (\theta_d + \beta) & \theta_d < -\beta \end{cases} \tag{4}$$

where $\beta \geq 0$ is the dead-zone width. The viscous friction is shown in both sides, motor and load, of the feed drive system by c_m and c_l, respectively. See Fig. 4 for further depiction of values mentioned above [Nordin and Gutman [14] and Sugie, *et al.* [15]).

CONTROL OF MACHINE TOOL FEED DRIVES WITH BACKLASH

Traditional Control Techniques

Academia has been dealing with the non-linear problem of backlash since quite a while. Naturally, usage of conventional linear techniques for motion control systems would be the first refuge for researchers to tackle this prominent hurdle. The feed drive system which has been represented by the set of equations (1), by the aid of the backlash representation in Fig. 5, can be formulated into state-space representation for control design studies as follows:

$$\dot{x}_m(t) = A_m x_m(t) + B\big(u(t) - \vartheta(t)\big) \tag{5}$$

$$\dot{x}_l(t) = A_l x_l(t) + B_l\,\vartheta(t) \tag{6}$$

Where the motor and load state variable vectors are, respectively, given by

$$x_m^T = [\theta_m \quad \dot{\theta}_m], \qquad x_l^T = [\theta_l \quad \dot{\theta}_l], \tag{7}$$

and the matrices in equations (5) and (6) are defined as follows:

$$A_m = \begin{bmatrix} 0 & 1 \\ 0 & -\dfrac{c_m}{J_m} \end{bmatrix}, A_l = \begin{bmatrix} 0 & 1 \\ 0 & -\dfrac{c_l}{J_l} \end{bmatrix}, B = \begin{bmatrix} 0 & 1/J_m \end{bmatrix}^T \text{ and } B_l = \begin{bmatrix} 0 & 1/J_l \end{bmatrix}^T. \tag{8}$$

The control process involves two main modes of operation, in which two controllers are to be interchanged; backlash-phase and contact-phase controllers. In backlash phase, $\vartheta(t) = 0$, the load and motor dynamics represented by equations (5) and (6) are decoupled. Physically, this phenomenon is obviously sensed, due to the fact that the motor does fail to supply motion to the load in that instant. When $\vartheta(t) \neq 0$, the feed drive system halves are brought back to a coupling condition, i.e., is in the contact phase.

Traditionally, PID controllers have been seen mostly dominating machine tool feed drive system control literature due to the fact that the integral part highly enhances error readings when implemented to the system. The PID controller can be realized as a function of error as follows:

$$u(t) = K_P e(t) + K_I \int e(t)\,dt + K_D \frac{d}{dt} e(t) \tag{9}$$

where $e(t)$ is the position error – difference between reference and measured values, K_P is the proportional gain, K_I is the integral gain, and K_D is the derivative gain. PI controllers have been conventionally used in machine tool feed drives for both contact and non-contact regions, where the integral part compensate for the loading cutting forces, eliminate transients and reduce limit cycles produced due to backlash.

Model-based Control Techniques

The main purpose of using model-based control techniques is to compensate for the effect of backlash outside the region of backlash. Such a technique supports the usage of a specialized controller which handles backlash nonlinearity, and provides harmony to the controlled system while receiving control signal from two different controllers. Since it is model-based, then the backlash model should reflect on the controller and describe the resulting effects on the contact region by adding or subtracting the value of backlash off the input, according to the direction change of velocity. In the contact zone, the position controller that controls the motor-side position of the machine tool feed drive system. Reference signal to be used as a comparison domain, the control law depending on the previously explained technique is shown below:

$$u_{C_I} = J_m(\ddot{\theta}_{ref} - K_1(\dot{\theta}_m - \dot{\theta}_{ref} \pm \beta) - K_2(\theta_m - \theta_{ref} \pm \beta) \quad (10)$$

Where K_1 and K_2 are tuning control gains. Also, β changes sign according to $\theta_m - \theta_l$ being negative or positive, respectively. Feedforward control can be implicitly contained within the controller as we can see above.

The motivation for the previously mentioned control law is that when $k_s = \infty$ and $\beta = 0$, dynamics of machine tool feed drive reduce to:

$$J_m \ddot{\theta}_m = u \quad (11)$$

which can be stabilized with any positive K_1 and K_2. This controller has been implemented and tested on different studies dealing with machine tool feed drive systems and showed good performance (Tao and Kokotović [9-11], Ling and Tao [16], Kokotović, *et al.* [17]).

In this study, we are going to deal with two new control laws to solve this problem. The two control laws are extentions derived from equation (10). The original equation (10) is considered in this study for the sake of comparison and will be denoted as the contact-zone controller type I. The following two equations represent the two control laws proposed in this study. They will be denoted as the contact-zone controller type II and III. The goal of the controllers II and III is to have better performance and improved accuracy as they confine the effect of inertia to acceleration component and add an integral part that will be of vital effect on transients of feed drive systems:

$$u_{C_{II}} = J_m \ddot{\theta}_{ref} - K_{1'}(\dot{\theta}_m - \dot{\theta}_{ref} \pm \beta) - K_{2'}(\theta_m - \theta_{ref} \pm \beta) \quad (12)$$

$$\begin{aligned} u_{C_{III}} = {} & J_m \ddot{\theta}_{ref}(t) - K_{1'}(\dot{\theta}_m(t) - \dot{\theta}_{ref}(t)) - K_{2'}(\theta_m(t) - \theta_{ref}(t) \pm \beta) \\ & - K_3 \int_0^t (\theta_m(t) - \theta_{ref}(t)) dt \end{aligned} \quad (13)$$

where $K_{1'}$, $K_{2'}$ and K_3 are tuning control gains. Also, β changes sign according to $\theta_m - \theta_l$ being negative or positive, respectively. In backlash zone, this type of control is also used for backlash compensation due to the same advantages mentioned before. The motor position is controlled with respect to the load instead of the reference input, since feed drive system load- and motor- sides become decoupled from each other when backlash takes place. Control law can be introduced in the following form:

$$u_{B_I} = J_m(\ddot{\theta}_l - K_4(\dot{\theta}_m - \dot{\theta}_l \pm \beta) - K_5(\theta_m - \theta_l \pm \beta) \quad (14)$$

Where K_4 and K_5 are tuning control gains. Also, β changes sign according to $\theta_m - \theta_l$ being negative or positive, respectively.

In this study, same as the last subsection, we are going to deal with two new control laws to solve this problem. The two control laws are modifications made to the backlash controller (14) which will be used in this study for the sake of comparison with the two backlash controllers proposed in this study. It will also be denoted as the backlash-zone controller type I. The following two equations represent the two proposed control laws as they are denoted by the backlash-zone controllers type II and III:

$$
\begin{aligned}
u_{B_{II}} &= J_m\ddot{\theta}_{ref} - K_{4'}(\dot{\theta}_m - \dot{\theta}_{ref} \pm \beta) \\
&\quad - K_{5'}(\theta_m - \theta_{ref} \pm \beta)
\end{aligned} \tag{15}
$$

$$
\begin{aligned}
u_{B_{III}} &= J_m\ddot{\theta}_{ref}(t) - K_{4'}(\dot{\theta}_m(t) - \dot{\theta}_{ref}(t)) - K_{5'}(\theta_m(t) - \theta_{ref}(t) \pm \beta) \\
&\quad - K_6 \int_0^t (\theta_m(t) - \theta_{ref}(t))dt
\end{aligned} \tag{16}
$$

where $K_{4'}$, $K_{5'}$ and K_6 are tuning control gains. Also, β changes sign according to $\theta_m - \theta_l$ being negative or positive, respectively.

SUPERVISORY CONTROL

A feed drive system can be modeled as a multi-inertia system with the inertias connected by dampers and springs; two-mass system is mainly used when backlash is the main interest of analysis. When dealing with backlash as a scope of analysis, it has two distinct operational areas where control of feed drives changes its approach of having a stable process. The control functionality in the contact zone is dedicated to achieving the best possible tracking performance. While, in the backlash (non-contact) zone, the control functionality will be devoted to bring the system back in contact as fast and effective as it can. The contact-mode controller is usually a simple PID or a model-based controller. While the backlash-mode controller is usually designed by the use of an appropriate control design method, e.g., linear control techniques, optimal control, etc. The property of bringing the system's disturbed state back to its initial value must be guaranteed. In our study, both controllers in both zones of operation are of a model-based type. The whole supervisory control process is schematically shown in Fig. 6.

The control process can be discussed from the top down. Switching amongst various system structures is essential to fulfill the unique task of control by overcoming obstacles and barriers encountered when using linear control techniques. Stability of the whole system containing more than one controller is quite paramount condition for the whole structure to work in harmony and consistency. Separate stability conformance for switched entities is not enough for the entire system to be considered stable. In our case, the plant dynamics matrices (equation (8)) A_i, $i = l, m$ are stable, i.e., all eigenvalues of those matrices are in the left-half complex plane. If all A_i's share a common Lyapunov function $V(x) = x^T Px$, such that $\dot{V}(x) = -x^T Qx$, $Q > 0$, where P and Q are design matrices to assure that quadratic form of the state x is positive definitive, then the system is proved exponentially stable. Exponential stability can be realized via the following formula (DeCarlo *et al.* [18]):

$$
|x(t)| \le \alpha_1 e^{-\alpha_2 t} |x(0)| \tag{17}
$$

where α_1 and α_2 are constants. The previous serves as conditions placed on $V(x)$ which are equivalent to $A_i^T P + PA_i = -Q$ for all i. To check for a common quadratic Lyapunov solution to prove the previously mentioned condition, the following two-inertia systems can be stated based on equations (5) and (6):

$$\begin{aligned} \dot{x}_m &= A_m x_m + B_m(u - \vartheta) \\ \dot{x}_l &= A_l x_l + B_l \vartheta \end{aligned} \tag{18}$$

Where u is the control signal, i.e. the driving torque, ϑ is the torque produced due to torsional flexibility and internal damping. In our study we assumed zero internal damping, bearing in mind that the models described above is realized using state-space formulation. The need for switching is called on by the presence of two different system characteristics that result in two different models of a machine tool feed drive system; i.e. when backlash occurs, $\vartheta = 0$.

SIMULATION RESULTS

The following results are achieved using various techniques to check for validity of the supervisory control approach as a paramount part of the physical and control layers within UROCA architecture. Testing should resemble real-life applications the way the input is fed through in the system. Machine tool feed drives usually receive either linear, circular or spline interpolation points as input values. Reference input in cases of linear interpolation with a specific federate, f, can be assigned to simulation by applying ramp signal with a slope value equals to the required feedrate. While reference input in cases of circular interpolation with specific feedrate can be assigned to simulation by having two sinusoidal signal sources having 90 degrees phase lag and identical amplitude equals the circular path radius r. This can be interpolated as follows:

$$X = r \times \cos\left((f / r / 60) \times t\right) \tag{19}$$

$$Y = r \times \sin\left((f / r / 60) \times t\right) \tag{20}$$

where t denotes time. The feed drive model used was a generic two-inertia system with a torsional stiffness in the middle (Matsubara *et al.* [13] and Ebrahimi *et al.* [19]). Disturbances of all kinds were excluded in simulation. Friction and damping were considered zero in order to only explore the backlash issue. A MATLAB/Simulink code was developed for conducting the simulation process. A non-backlash feed drive system produces smother circular path as indicated in Fig. 7a. Essentially, backlash generates limit cycles all over operation as one of the most important issues that have been noticed as shown in Fig. 7b. The fluctuation in output occurs during the backlash zone and the limit cycles are induced even over the contact zone, *see* Fig. 8. The model, which is used here to describe the machine tool feed drive system, consists of two-inertia system as previously explained in Section Two by equations (1) and (2). The dead zone model is used to represent the backlash nonlinearity as was previously explained in equations (4). The feed drive system parameters, where identical *x*- and *y*- axes are considered, are shown in Table 1.

Table 1 Parameters of the feed drive system.

Parameter	Value
J_m	5.2×10^{-3} $\mathrm{kg\cdot m^2}$
J_l	4.4×10^{-3} $\mathrm{kg\cdot m^2}$
K_s	950 N·m/rad
β	25, 12.5 μm
r	0.025 m
l	0.016 m/rev

When simulating feed drive systems with backlash, circular interpolation testing is of great significance at exploring the relative performance capabilities of the proposed controllers. To produce an arc or a circle, both axes work simultaneously with sinusoidal inputs. Our measure is the error between reference and output signals which also behaves the same way the velocity (feedrate) behaves. The feedrate indication is considered important due to the fact that inconsistency in feedrate would lead to a non-uniform surface quality and many other issues like tool wear.

The following control testing have been conducted in this study: (i) a traditional PI control scheme, (ii) switching scheme I that utilizes contact-zone and backlash controllers as introduced in equations (10) and (14), respectively, (iii) switching scheme II that utilizes contact-zone and backlash controllers as introduced in equations (12) and (15), respectively, and (iv) switching scheme III that utilizes contact-zone and backlash controllers as presented in equations (13) and (16), respectively. Testing has been taken under different feedrates applied to the axes of motion. The controller gains used in our implementation are shown in Table 2:

Table 2 Controller gain values.

Gain	Value	Gain	Value
K_1	10000	$K_{1'}$	1000
K_2	2000	$K_{2'}$	200
K_4	10000	$K_{4'}$	1000
K_5	2000	$K_{5'}$	200
K_3	25	K_6	25

The difference between the adapted control Type I and our proposed control Types II and III is shown in Fig. 9. Our controllers Type II and III reduce the inconsistent performance of the Type I controller regarding the output feedrate that is indeed a bad reflection on surface quality. Error in the previous example hits in between the interval ± 0.936217 m/min, which yields 11.703% of error. For higher speeds, higher error percentages are believed to be the main cause of unsatisfactory surface quality. Zooming at switching scheme II and III in particular, *see* Fig. 10, the fluctuations along both axes, produced while under switching scheme II, have been cleared out by the use of the integral action in switching scheme III.

As shown previously, another type of comparison was found to be essential; the output feedrate. Figures 11, 12 and 13 show the output feedrate variations due to the effect of backlash. Simulation time has been considered from 1 to 10 seconds in order to cancel the transient effects. Best results have been achieved using switching scheme III as clearly shown by Figure 13. The effect of backlash has been reduced to the minimum extent and the output has had low-magnitude equally spanned pulses along the feedrate function. The exchange process of controllers – switching, explains this; a completely smooth switching process is impossible to reach. In switching schemes I and II, it seems that those virtual pulses propagate into higher-magnitude fluctuations without a tangible pattern causing improper feedrate variations.

After introducing the integral part in the control scheme III, transients were suppressed as discernibly perceived by the schemes I and II. While Error values of the controller III for different feedrate inputs are quite the same as those of switching control scheme II. The produced feedrate is quite stable in magnitude with patterned pulse-like small variation (0.027 m/min compared to 0.25 m/min in scheme I). On the other hand, machine tool feed drive system has been brought forth to steady state in a tremendously fast manner introducing an excellent and successful switching criterion to solve and compensate for the prominent problem of backlash. All of the proposed schemes have shown great improvement in comparison with the standard PI controller, i.e., 32.6 μm compared to 946.3 μm. In switching schemes we are proposing, an error reduction of 53.6-54.5% with regard to the control laws introduced by Tao and his associates in many publications [9-11]. Also, highly-improved overall feedrate output has been achieved; less than 10% of feedrate fluctuations were attained. Scheme III has earned the best performance in position and feedrate outputs due to the nature of the implemented control algorithm.

CONCLUSION

Different switching schemes, built on a performance-based manner, have been formulated, introduced and simulated to solve for the nonlinear phenomenon of backlash. The whole approach has been formulated within the context of supervisory control theory developed for suppressing the nonlinear effects of feed drive systems with backlash. Results were shown and discussed throughout the study.

Application of supervisory control principles to earn improved results as expected outcomes of such an approach. This can be visualized by a stable and consistent process while changing from one controller to another due to change in needed functionality. Moreover, the performance of the supervisory control unit successfully switches from one controller to another according to signals measured, and based on that, mathematical operations are undertaken to decide when to switch on or off the backlash controller, and hence, the required control signal is generated. Switching in Scheme III shows the optimal case, with regards to the instance of switching and its effect on the whole system, where reflections on feedrate are highly noticeable; i.e., fluctuations are minimized drastically compared to those in Scheme I and II. This is considered as an aspect of reconfiguration at the control level that satisfies the objectives of our UROCA project at the physical and control layers. Such a centralized supervisory technique – a technique that is applied for each axis of motion separately – would prepare the feed drive system to be ready for decentralized control approaches, such as cross-coupling controllers.

All of the previous points emphasize that the output of this work depicts a reconfiguration aspect on the control process level for machine tools as perceived, investigated and resolved by the physical and control layers located at the delibrative brain of UROCA architecture.

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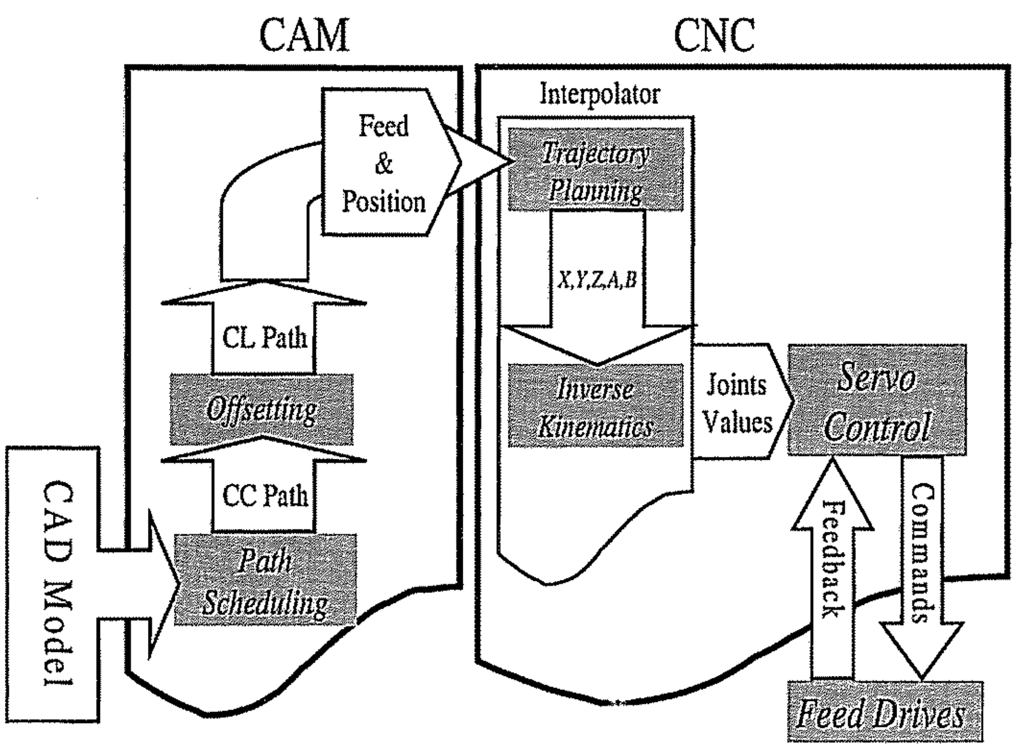


Fig. 1 Nature of Information Transfer of A CAM/CNC Stage of Product Synthesis.

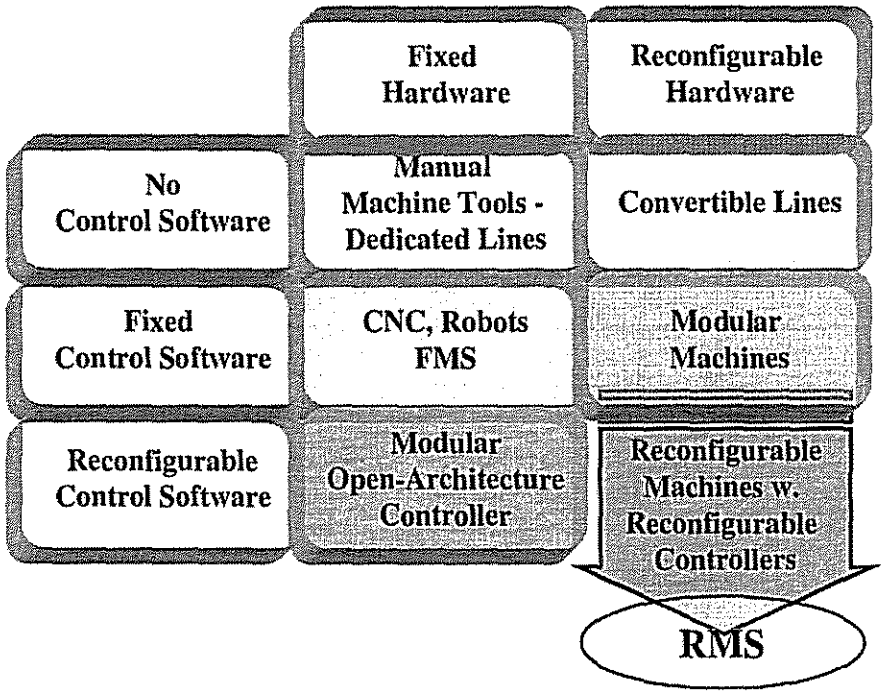


Fig. 2 Development Matrix of Software Versus Hardware For Machine Tools.

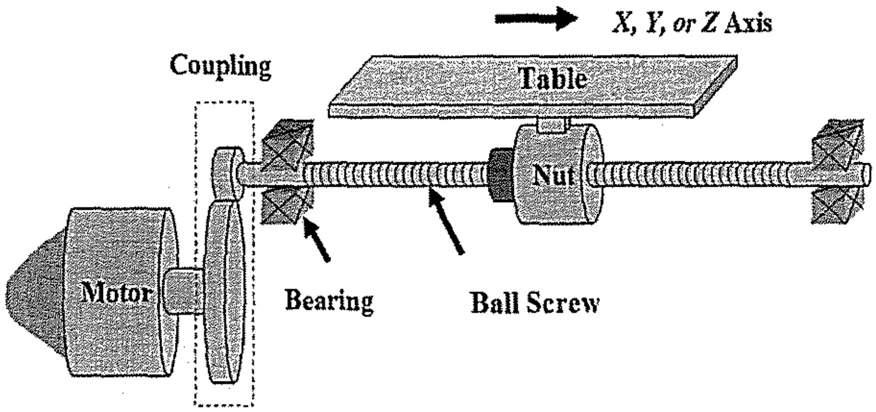


Fig. 3 Schematic Diagram of a Typical Machine Tool Feed Drive.

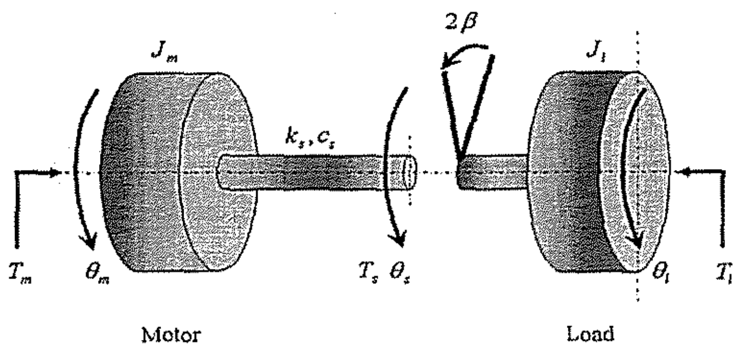


Fig. 4 Backlash in Two-Inertia System.

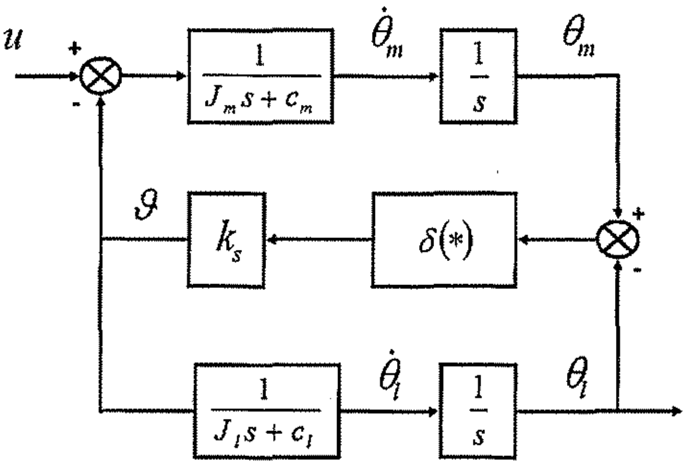


Fig. 5 Machine Tool Feed Drive System With Backlash.

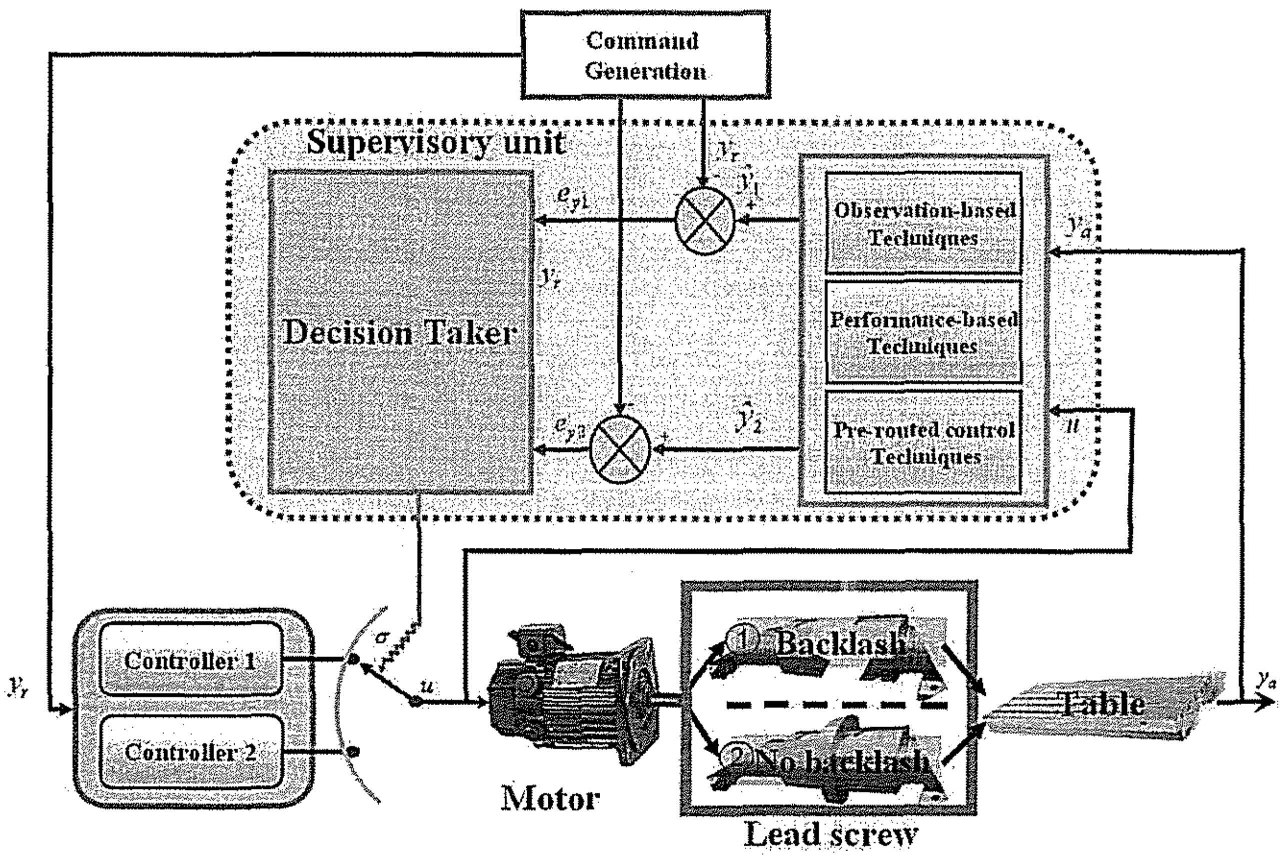
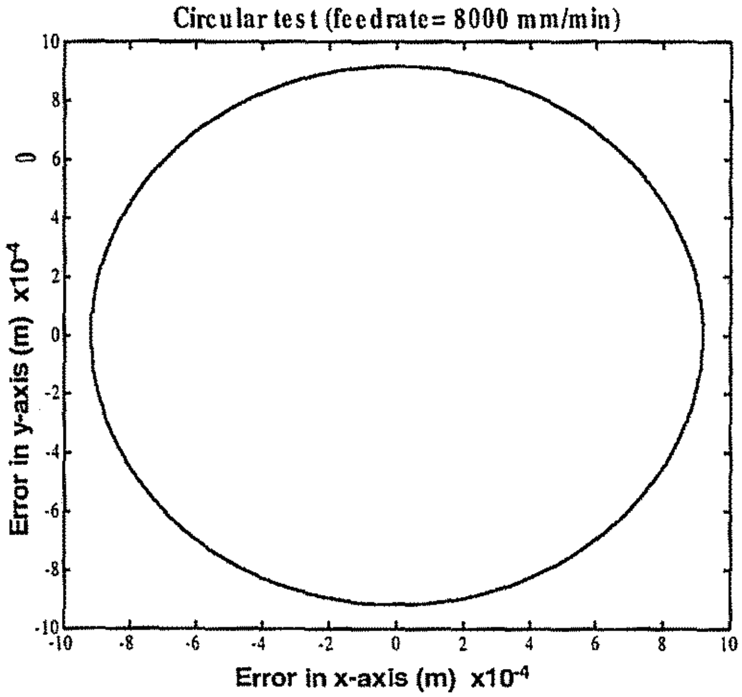


Fig. 6 Schematics Of A Supervisory Backlash Compensation.

a)



b)

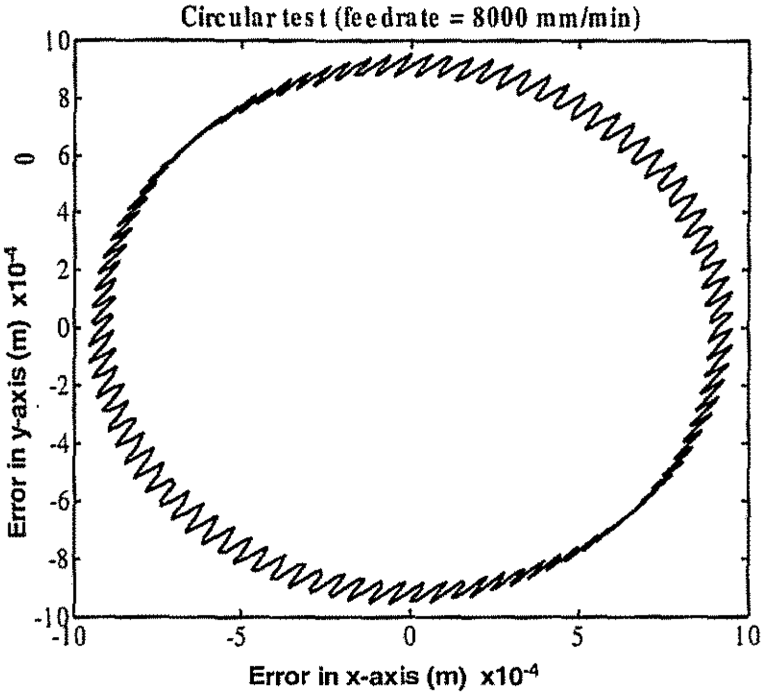


Fig. 7 Feed drive circular test with PI controller (feedrate = 8000 mm/min) using a model: a) excluding backlash. b) with 25μm backlash.

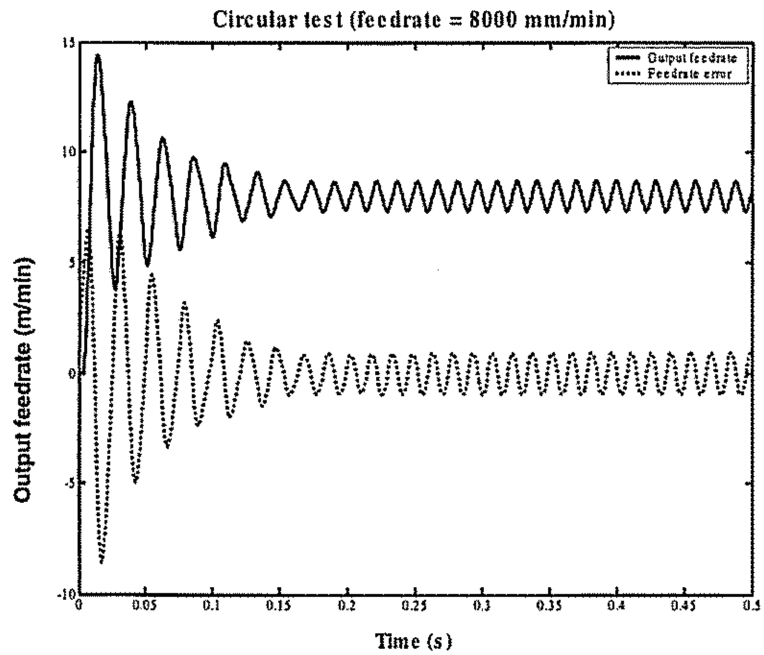


Fig. 8 Feed drive circular test with PI controller (feedrate = 8000 mm/min) with 25 μ m backlash.

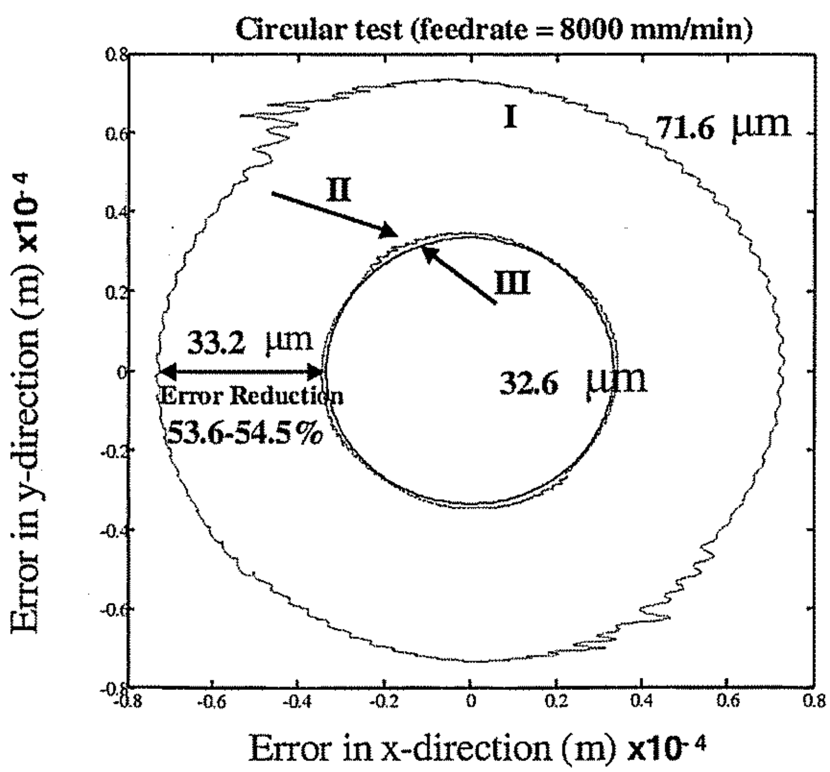


Fig. 9 Comparison among the three switching schemes at a feedrate of 8000 mm/min.

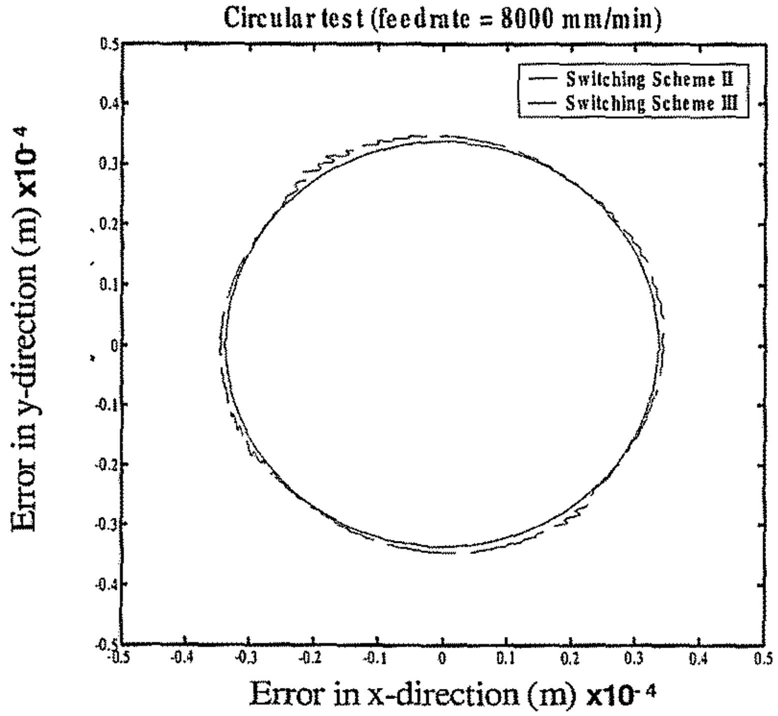


Fig. 10 A Zoomed View at Switching Schemes II And III at Feedrate of 8000 Mm/Min.

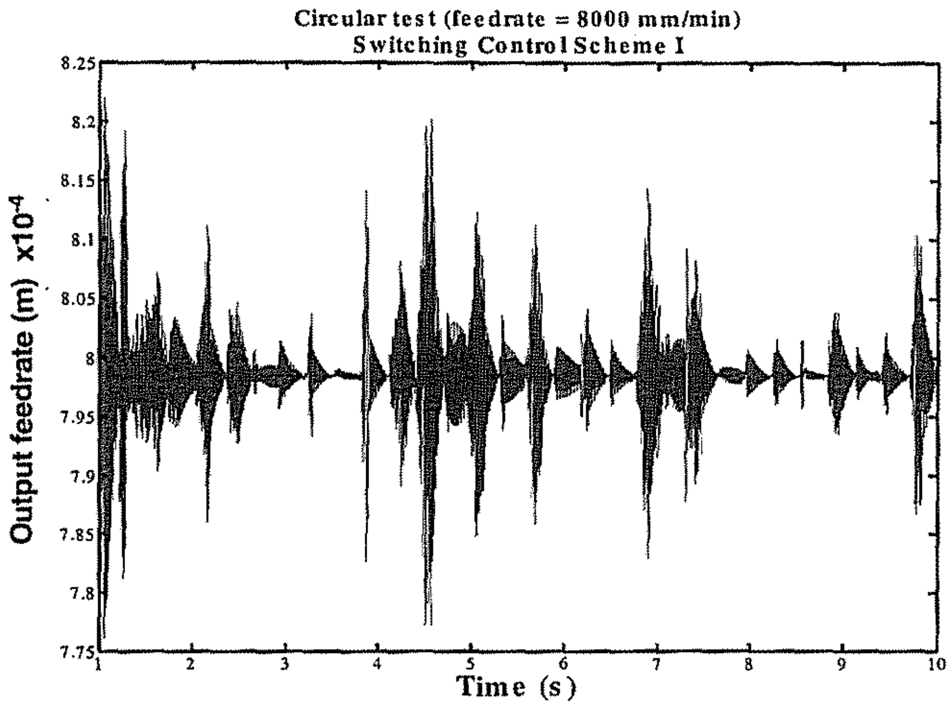


Fig. 11 Overall feedrate output using switching scheme I.

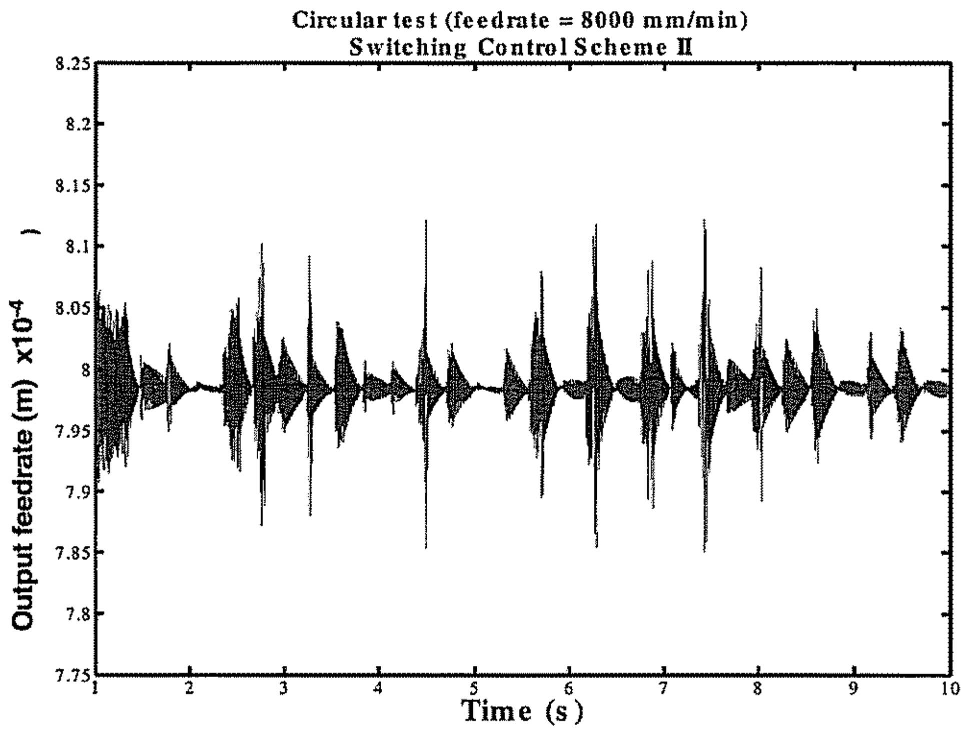


Fig. 12 Output feedrate output using switching scheme II.

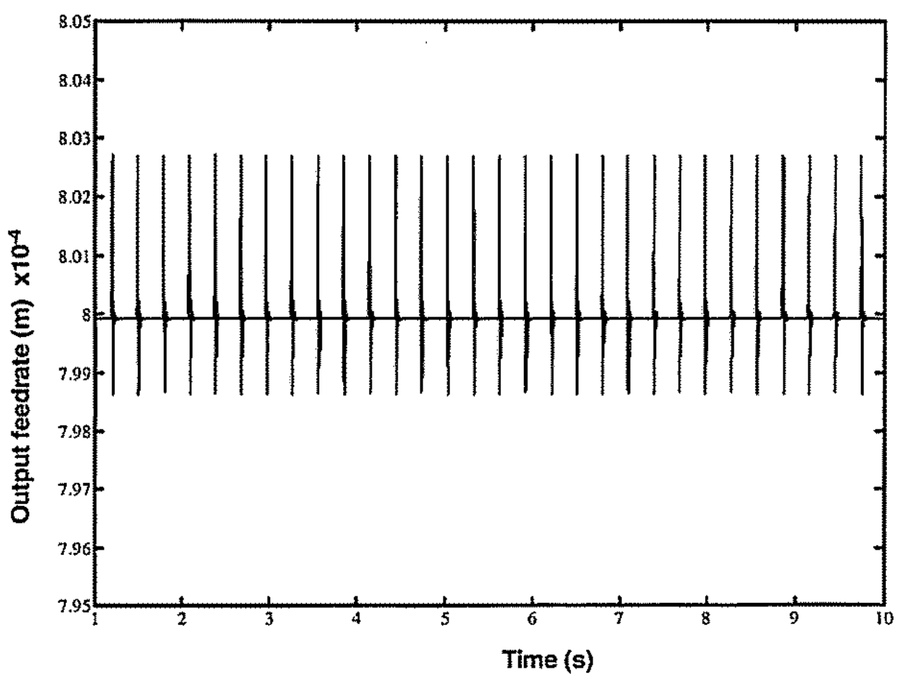


Fig. 13 The output overall feedrate using switching scheme III.