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Kombiniran sistem ločenega optimiranja in prilagodnega nastavljanja rezalnih parametrov med procesom oblikovnega frezanja

A Combined System for Off-Line Optimization and Adaptive Adjustment of the Cutting Parameters During a Ball-End Milling Process

Uroš Župerl - Franci Čuš - Edi Kiker - Matjaž Milfelner

V prispevku je prikazana uporaba združevanja metod nevronskih mrež in mehke logike pri modeliranju in prilagodnem krmiljenju postopka oblikovnega frezanja. Izdelan je celovit postopek hibridnega modeliranja postopka odrezovanja (sistem ANfis), ki ga uporabimo pri izdelavi simulatorja frezanja RNK. S hibridnim modeliranjem postopka, ločeno optimizacijo ter usmerjeno nevronsko krmilno shemo (UNKS) je zgrajen kombiniran sistem za posredno optimiranje in prilagodno nastavljanje rezalnih parametrov. To je prilagodni sistem krmiljenja, ki z digitalno prilagodljivostjo rezalnih parametrov nadzoruje rezalno silo in ohranja stalno hrapavost obdelane površine med frezanjem. Tako uravnoteži vse motnje postopka odrezovanja: obrabo orodja, nehomogenost obdelovanega materiala, vibracije, drdranje itn. Poglavitno načelo vodenja je izvedeno s krmilno shemo (UNKS), ki jo sestavljata dve nevronski razpoznavali dinamike postopka in primarni krmilnik. Simulator frezanja RNK testira stabilnost sistema in uglasi parametre krmilne sheme. Postopek je bil uspešno uporabljen na RNK frezalnem stroju Heller. S preizkusi je potrjena učinkovitost prilagodnega sistema krmiljenja, ki se kaže v izboljšani kakovosti površine in manjši obrabi orodja.

(Ključne besede: odrezovanje, krmiljenje sil, sistemi prilagoditveni, optimiranj, frezanje oblikovno)

This paper discusses the use of combining the methods of neural networks, fuzzy logic and PSO evolutionary strategy in modelling and adaptively controlling the process of ball-end milling. An overall procedure for the hybrid modelling of the cutting process (ANfis-system) used for working out the CNC milling simulator has been prepared. On the basis of the hybrid process modelling, off-line optimization and feed-forward neural control scheme (UNKS) the combined system for off-line optimization and adaptive adjustment of the cutting parameters is built. This is an adaptive control system controlling the cutting force and maintaining the constant roughness of the surface being milled by digital adaptation of the cutting parameters. In this way it compensates for all the disturbances during the cutting process: tool wear, non-homogeneity of the workpiece material, vibrations, chatter etc. The basic control principle is based on a control scheme (UNKS) consisting of two neural identificators of the process dynamics and the primary controller. The CNC milling simulator tests the system stability and tunes the control-scheme parameters. The approach was successfully applied to a Heller CNC milling machine. Experiments have confirmed the efficiency of the adaptive control system, which was reflected in improved surface quality and decreased tool wear.

(Keywords: machining, force control, adaptive control systems, optimization, ball-end mill)

0 UVOD

Pomanjkljivost modernih RNK sistemov je, da se rezalni parametri, kakor so podajanje, rezalna hitrost in globina reza, še vedno programirajo v ločenem načinu. Rezalni parametri so običajno izbrani

0 INTRODUCTION

A drawback of modern CNC systems is that the machining parameters, such as feedrate, cutting speed and depth of cut, are still programmed off-line. The machining parameters are usually selected pred obdelavo na podlagi programerjevih izkušenj in tehnoloških priročnikov. Da bi preprečili poškodbe orodja in se izognili lomu orodja, so rezalne razmere običajno izbrane skrajno zadržano, kar pomeni, da so vrednosti podajanja in rezalne hitrosti mnogo nižje od priporočenih vrednosti, ki jih je podal proizvajalec orodja. S tem so sicer izpolnjene omejitve obdelave, vendar pa stroj in orodje nista popolnoma izkoriščena.

Zato so mnogi RNK sistemi neučinkoviti in obratujejo v rezalnih razmerah, ki so daleč od optimalnih. Četudi so rezalni parametri določeni v ločenem načinu z ne-determinističnimi optimizacijskimi algoritmi, ki temeljijo na umetni inteligenci (nevronske mreže) [1], jih pozneje med obdelavo ni več mogoče popraviti.

Da bi zagotovili kakovost obdelanih kosov, zmanjšali stroške obdelave in povečali učinkovitost obdelave, je treba prilagajati rezalne parametre med postopkom obdelave (v dejanskem času), tako da so izpolnjeni optimalni kriteriji obdelave. Zato raziskovalci intenzivno preučujejo prilagodne sisteme krmiljenja (PKS - AC), ki omogočajo sprotno prilagajanje rezalnih razmer [2]. V našem PKS se podajanje nastavlja v sprotnem načinu z namenom, da se ohranja stalna rezalna sila kljub spremembam rezalnih razmer.

V središču te raziskave je krmiljenje največje sile pri 4-osni RNK obdelavi z uporabo ločenih optimiranih hitrosti podajanja in prilagodnega krmiljenja. V tem prispevku je razvit nevronski prilagodni sistem krmiljenja in izvedeno je nekaj simulacij ter preizkusov z nevronsko strategijo krmiljenja. Rezultati prikazujejo zmožnost predlaganega sistema za učinkovito krmiljenje največjih rezalnih sil v rezalnih razmerah, ki so pogoste pri opravilih oblikovnega frezanja.

Številni raziskovalci so razvijali in ocenjevali algoritme za krmiljenje rezalne sile. Med najbolj razširjenimi je PI krmilnik s stalnim ojačanjem, ki sta ga za frezanje prvotno predlagala Tlusty in Elbestawi [3]. Stute in Goetz [4] sta predlagala PI krmilnik z nastavljivim ojačanjem, kjer se ojačanje krmilnika prilagaja kot odziv na spremembe rezalnih razmer. Čisti prilagodni modelno podprt referenčni sistem krmiljenja (MPRKS - MRAC) je prvotno raziskoval Tomizuka [5]. Liu [6] je te sisteme simuliral, ocenil ter fizično uresničil. V obeh raziskavah je ugotovljeno, da vsi trije prilagodni sistemi krmiljenja delujejo bolje kakor PI krmilnik s stalnim ojačanjem. Žal samo prilagodno krmiljenje ne more učinkovito krmiliti

before machining according to the programmer's experience and machining handbooks. To prevent tool damage and to avoid machining failure the operating conditions are usually set extremely conservatively, which means that the values of the feeding and the cutting speed are much lower than the recommended values specified by the tool maker. Thus, although the machining constraints are fulfilled, the tool and the machine are not fully utilized.

As a result, many CNC systems are inefficient and run under operating conditions that are far from optimised. Even if the machining parameters are determined off-line by non-deterministic optimisation algorithms based on artificial intelligence (neural networks) [1], they cannot be adjusted further during the machining process.

To ensure the quality of machining products, to reduce the machining costs and increase the machining efficiency, it is necessary to adjust the machining parameters during the machining process (in real-time), to satisfy the optimal machining criteria. For this reason, adaptive control (AC), which provides on-line adjustment of the operating conditions, is being studied with interest [2]. In our AC system, the feedrate is adjusted on-line in order to maintain a constant cutting force in spite of variations in the cutting conditions.

The focus of this research is peak-force regulation in 4-axis CNC machining through the use of off-line optimized feedrates and adaptive control. In this paper, a neural adaptive controller is developed and some simulations and experiments with the neural control strategy are carried out. The results demonstrate the ability of the proposed system to effectively control peak forces for the cutting conditions commonly encountered in end-milling operations.

Force-control algorithms have been developed and evaluated by numerous researchers. Among the most common is the fixed-gain proportional integral (PI) controller, originally proposed for milling by Tlusty & Elbestawi [3]. Stute & Goetz [4] proposed an adjustable-gain PI controller, where the gain of the controller is adjusted in response to variations in the cutting conditions. The purely adaptive model reference adaptive controller (MRAC) approach was originally investigated by Tomizuka [5]. These controllers were simulated and evaluated and physically implemented by Liu [6]. Both studies found all three parameter adaptive controllers to perform better than the fixed-gain PI controller. Unfortunately, adaptive control alone cannot effectively control the cutting forces.

rezalnih sil. Do zdaj ni takega krmilnika, ki bi se lahko dovolj hitro odzval na nenadne spremembe geometrijske oblike reza in odpravil velike konice rezalnih sil. Zato uporabimo sprotno prilagodno krmilje v povezavi z ločenim optimiranjem. Optimiranje se izvede z algoritmom, ki ga je izdelal Župerl [7].

Mnogo dela je bilo opravljenega na področju prilagodnega krmiljenja rezalnih sil pri frezanju ([8] in [9]). Vendar se v večini predhodnih del problem frezanja poenostavi v enorazsežno frezanje. V tem prispevku bomo obravnavali problematiko krmiljenja sile pri trirazsežnem frezanju.

V naslednjem poglavju je na kratko opisana celovita strategija krmiljenja rezalne sile. Četrto poglavje obravnava simulator RNK frezanja. V petem poglavju je s preizkusi ocenjen kombiniran prilagodni sistem krmiljenja. Na koncu so v sedmem in osmem poglavju podani rezultati preizkusov, sklepi in priporočila za nadaljnje raziskave.

1 KOMBINIRAN SISTEM ZA LOČENO OPTIMIZACIJO IN PRILAGODNO KRMILJENJE REZALNE SILE

Poglavitna zamisel tega postopka je združiti algoritem ločene optimizacije rezalnih razmer in prilagodnega krmiljenja sile (sl. 1). Na podlagi tega novega kombiniranega sistema vodenja je mogoče laže in natančneje nadzorovati zapletene postopke kakor s standardnimi postopki krmiljenja. Cilj razvitega kombiniranega sistema krmiljenja je zagotavljati čim večjo stopnjo odvzemanja materiala (SOM - MRR) in ohranjati rezalno silo na ravni primerjalne vrednosti. Kombinirani sistem krmiljenja se s prilagoditvijo podajanja avtomatsko prilagaja trenutnim rezalnim razmeram. Kadar so obremenitve vretena majhne, sistem poveča podajanje prek predprogramiranih vrednosti, kar ima za posledico znatno zmanjšanje časa obdelave in proizvodnih stroškov. Kadar so obremenitve vretena velike, se podajanje zmanjša, kar zavaruje rezalno orodje pred poškodbami in lomom. Kadar sistem zazna skrajne sile, avtomatsko zaustavi stroj, da zaščiti rezalno orodje. Sistem zmanjša potrebo po nenehnem nadzoru operaterja. Spodaj je podano zaporedje korakov pri sprotni optimizaciji postopka frezanja.

1. Priporočene rezalne razmere se določijo z ANfis (prilagodni nevromehki sklepni sistem) modeli, ki so glavni elementi programske opreme za izbiro priporočenih rezalnih razmer.

There is no controller that can respond quickly enough to sudden changes in the cut geometry to eliminate large spikes in the cutting forces. Therefore, we have implemented on-line adaptive control in conjunction with off-line optimization. The optimization is performed with an algorithm developed by Župerl [7].

Much work has been done on adaptive cutting-force control for milling [8] and [9]. However, most of the previous work has simplified the problem of milling into one-dimensional motion. In this contribution we will consider force control for three-dimensional milling.

The following section briefly describes the overall cutting-force control strategy. Section four covers the CNC milling simulator. Section five describes the experimental evaluation of the combined adaptive-control system. Finally, sections seven and eight present the experimental results, the conclusions, and the recommendations for future research.

1 COMBINED SYSTEM FOR OFF-LINE OPTIMIZATION AND ADAPTIVE CUTTING-FORCE CONTROL

The basic idea of this approach is to merge the off-line cutting condition optimization algorithm and adaptive force control (Fig. 1). Based on this new, combined control system, very complicated processes can be controlled more easily and accurately compared to standard approaches. The objective of the developed combined control system is keeping the metal removal rate (MRR) as high as possible and maintaining the cutting force as close as possible to a given reference value. The combined control system is automatically adjusted to instant cutting conditions by adaptation of the feedrate. When spindle loads are low, the system increases feeds above and beyond pre-programmed values, resulting in considerable reductions in the machining time and production costs. When spindle loads are high the feedrates are lowered, safeguarding the cutting tool from damage and breakage. When the system detects extreme forces, it automatically stops the machine to protect the cutting tool. This reduces the need for constant operator supervision. The sequence of steps for on-line optimization of the milling process is presented below.

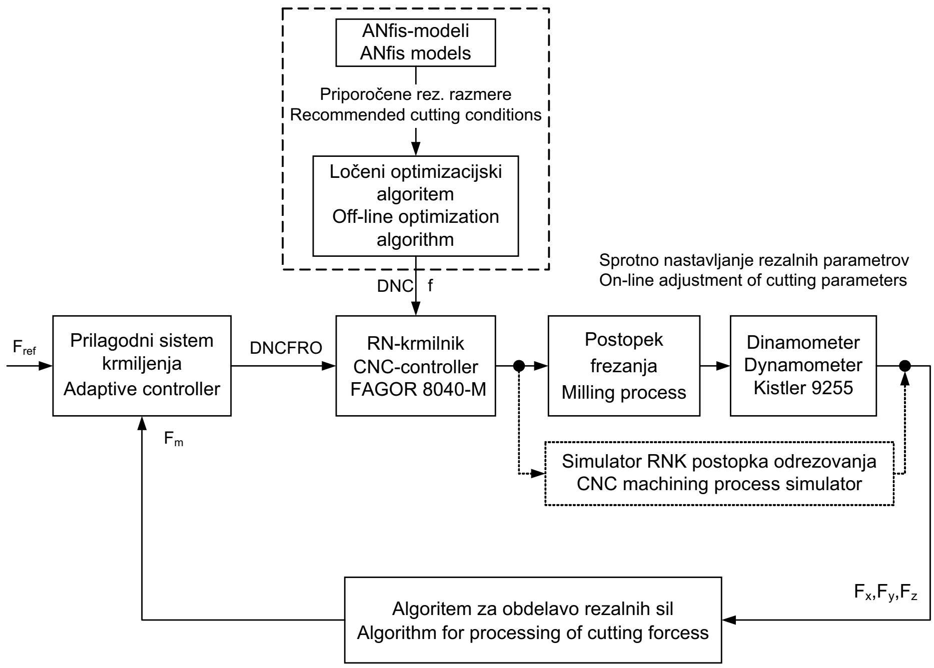
1. The recommended cutting conditions are determined by ANfis (adaptive neuro-fuzzy inference system) models, which are basic elements of the software for selecting the recommended cutting conditions.

2. Predprogramirane vrednosti podajanja, določene z algoritmom ločene optimizacije, se pošljejo RN krmilniku frezalnega stroja. Optimizacijski algoritem [1] deluje na podlagi usmerjenih in radialnih mrež ob hkratni uporabi novih sodobnih algoritmov učenja, ki se avtomatično prilagajajo trenutnim razmeram med postopkom učenja. Glavni cilj algoritma je določiti takšne optimalne rezalne razmere (rezalno hitrost, podajanje in globino reza), ki čimbolj povečajo obseg proizvodnje, zmanjšajo obdelovalne stroške in izboljšajo kakovost izdelka.
3. Izmerjene rezalne sile se sporočajo nevronski krmilni shemi,
4. Nevronska krmilna shema prilagodi optimalne vrednosti podajanja in jih pošlje nazaj stroju.
5. Koraki 1 do 3 se ponavljajo do konca obdelave.

Nevronski prilagodni krmilnik sile prilagodi podajanje, tako da predpiše popravek vrednosti podajanja RN krmilniku 4-osnega Hellerja na temelju izmerjene največje vrednosti sile (sl. 1). Dejanska vrednost podajanja je zmnožek popravka podajanja (DNCFRO) in programirane stopnje podajanja. Če bi bila programska oprema za optimiranje rezalnih razmer popolna, bi optimirana vrednost podajanja

2. The pre-programmed feedrates determined by the off-line optimization algorithm are sent to the CNC controller of the milling machine. The optimization algorithm works on the basis of feed-forward and radial basis networks with the simultaneous use of a new, advanced learning algorithm that automatically adapts to current conditions during the training process. The main objective of the paper is to determine the optimal machining parameters (cutting speed, feedrate, depth of cut) that maximize the extent of production, reduce the manufacturing costs and finally improve the product quality.
3. The measured cutting forces are sent to the neural control scheme,
4. The neural control scheme adjusts the optimal feedrates and sends details back to the machine,
5. Steps 1 to 3 are repeated until the termination of the machining.

The neural adaptive force controller adjusts the feedrate by assigning a feedrate override percentage to the CNC controller on a 4-axis Heller, based on a measured peak force (see Figure 1). The actual feedrate is the product of the feedrate override percentage (DNCFRO) and the programmed feedrate. If the software for optimization of the cutting conditions was per-



Sl. 1. *Zgradba kombiniranega sistema za ločeno optimiranje in prilagodno nastavljanje rezalnih parametrov*

Fig. 1. *Structure of combined system for off-line optimization and adaptive adjustment of the cutting parameters*

vedno ustrezala primerjalni največji sili. V tem primeru bi bil popravek podajanja 100-odstoten. Da bi lahko krmilnik vodil največjo silo, mora biti podatek o sili na voljo algoritmu vsakih 20 ms. Ta podatek zagotavlja programska oprema za zbiranje podatkov (LabVIEW) in algoritem za obdelavo rezalnih sil. Čas optimiranja z ločenim optimizacijskim algoritmom, ki temelji na usmerjeni nevronski mreži, znaša 0,001 s. Kombinirani sistem krmiljenja najkasneje v 4 iteracijah (2ms) vrne vrednost rezalne sile na raven primerjalne - želene vrednosti.

2 USMERJENA NEVRONSKA KRMILNA SHEMA (UNKS)

Poglavitno načelo krmiljenja sloni na krmilni shemi (UNKS), ki je sestavljena iz treh delov (sl. 2). Prvi del je zanka, znana kot zunanja krmilna zanka s povratno zvezo (klasična krmilna zanka). Klasična krmilna zanka temelji na napaki med izmerjeno (F_m) in želeno rezalno silo (F_{ref}). Primarno krmilje klasične krmilne zanke je nevronska mreža (NM-R), ki posnema delovanje delilnega krmilnika.

Drugi del je zanka, povezana z nevronsko mrežo 1 (NM-1), ki predstavlja notranji model dinamike postopka. Deluje kot identifikator dinamike postopka. Ta del predstavlja notranjo zanko s povratno zvezo, ki je mnogo hitrejša od zunanje krmilne zanke, kajti slednja vsebuje zakasnitve merilnega člena.

Tretji del sistema je nevronska mreža 2 (NM-2). NM-2 se uči inverzne dinamike postopka.

UNKS deluje po naslednjem načelu: Zaznavna povratna zveza je učinkovita v glavnem v fazi učenja. Ta zanka daje klasični signal povratne zveze za krmiljenje postopka. Med fazo učenja se NM-2 uči obrnjene dinamike. Med učenjem notranja zanka postopoma prevzame vlogo zunanje krmilne zanke in primarnega krmilnika. Z napredovanjem učenja bo obrnjeni dinamični del nadomestil zunanjo krmilno zanko. Končni rezultat je, da je postopek krmiljen v glavnem z NM-1 in NM-2, ker je izhodna napaka postopka skoraj enaka nič.

To je prilagodni sistem krmiljenja, ki uravnava rezalno silo in ohranja stalno hrapavost frezane površine z digitalno prilagoditvijo rezalnih parametrov. Tako izravna vse motnje med postopkom odrezovanja: obrabo orodja, nehomogenost materiala obdelovanca, vibracije, drdranje itn.

fect, the optimized feedrate would always be equal to the reference peak force. In this case the correct override percentage would be 100%. In order for the controller to control the peak force, force information must be available to the control algorithm every 20ms. Data acquisition software (LabVIEW) and the algorithm for processing the cutting forces are used to provide this information. The optimization time with the use of the off-line optimization algorithm based on a feed-forward neural network, is equal to 0.001s. The combined control system returns the cutting-force value to the desired value level within four or less iterations at the latest.

2 FEED-FORWARD NEURAL CONTROL SCHEME (UNKS)

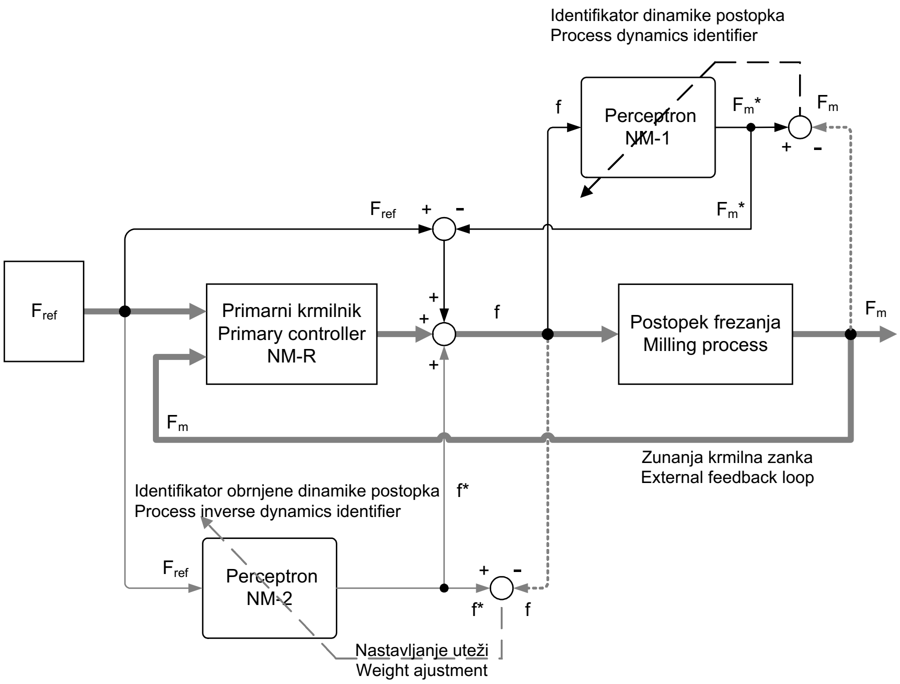
The basic control principle is based on a control scheme (UNKS) consisting of three parts (Fig. 2). The first part is the loop known as external feedback (conventional control loop). The feedback control is based on the error between the measured (F_m) and desired (F_{ref}) cutting force. The primary feedback controller is a neural network (NM-R) that imitates the work of the division controller.

The second part is the loop connected with neural network 1 (NM-1), which is an internal model of the process dynamics. It acts as the process dynamics identifier. This part represents an internal feedback loop, which is much faster than the external feedback loop, as the latter usually has sensory delays.

The third part of the system is neural network 2 (NM-2). The NM-2 learns the process inverse dynamics.

The UNKS operates according to the following procedure. The sensory feedback is effective mainly in the learning stage. This loop provides a conventional feedback signal to control the process. During the learning stage, NM-2 learns the inverse dynamics. As the learning proceeds, the internal feedback gradually takes over the role of the external feedback and the primary controller. Then, as learning proceeds further, the inverse dynamics part will replace the external feedback control. The final result is that the plant is controlled mainly by NM-1 and NM-2, since the process output error is nearly zero.

This is an adaptive control system controlling the cutting force and maintaining the constant roughness of the surface being milled by digital adaptation of the cutting parameters. In this way it compensates for all the disturbances during the cutting process: tool wear, non-homogeneity of the workpiece material, vibrations, chatter, etc.



Sl. 2. *Usmerjena nevronska krmilna shema (UNKS)*
Fig. 2. *Feed-forward neural control scheme (UNKS)*

3 SIMULATOR RNK FREZANJA

S simulatorjem RNK frezanja ocenimo izvedbo krmilnika še pred izvedbo eksperimentalnih preizkusov. S simulatorjem RNK frezanja preizkušamo stabilnost sistema in uglasimo parametre krmilne sheme vodenja. Simulator sestavlja nevronski model sil, model podajalnega pogona in model elastičnosti (sl. 3). Nevronski model napove rezalne sile na podlagi rezalnih razmer in geometrijske oblike reza, kakor je opisal Župerl [10]. Model podajalnega servopogona simulira odziv stroja na spremembe želenega podajanja. Model elastičnosti poda upogibanje orodja (sl. 3). Model je prirejen po Muršecu [11]. Elastičnost sistema je modelirana kot statični odklon frezala. Enačba elastičnosti za smer X poti orodja je:

3 CNC MILLING SIMULATOR

A CNC milling simulator is used to evaluate the controller design before conducting the experimental tests. The CNC milling simulator tests the system stability and tunes the control scheme parameters. The simulator consists of a neural force model, a feed-drive model and a model of elasticity (Fig. 3). The neural model predicts the cutting forces based on the cutting conditions and the cut geometry, as described by Župerl [10]. The feed-drive model simulates the machine response to changes in the desired feedrate. The elasticity model represents the deflection between the tool and the workpiece (Fig. 3). The model is adapted from Muršec [11]. The system elasticity is modelled as a static deflection of the cutter. The elasticity equation for the X direction of tool travel is:

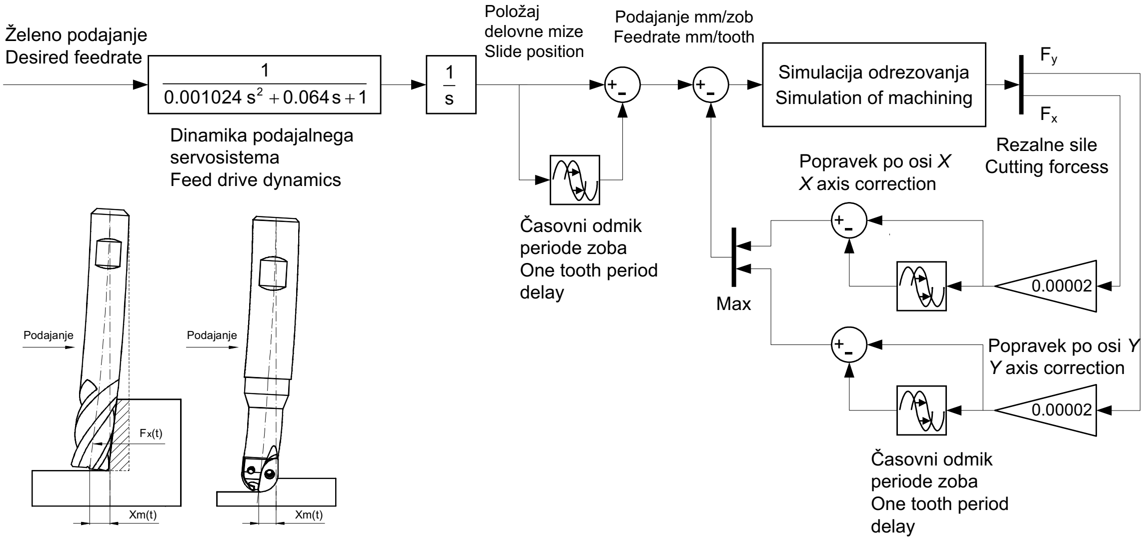
$$X_m(t) = (-F_x(t)) + F_x(t - T_{tp})) \cdot G_x \qquad (1),$$

kjer je X_m elastični odklon orodja, ki vpliva na debelino odrezka, F je rezalna sila, G_x je elastičnost, t je čas in T_{tp} je časovni odmik periode zoba.

Model podajalnega servopogona je določen s preizkusi, s preučevanjem odzivov sistema na skočne spremembe želene podajalne hitrosti. Model se najbolje ujema s sistemom drugega reda z

where X_m is the tool's elastic deflection affecting the chip thickness, F is the cutting force, G_x is the compliance, t is time and T_{tp} is the tool passing period.

The feed-drive model was determined experimentally by examining the responses of the system to step changes in the desired feed velocity. The best model fit was found to be a second-order



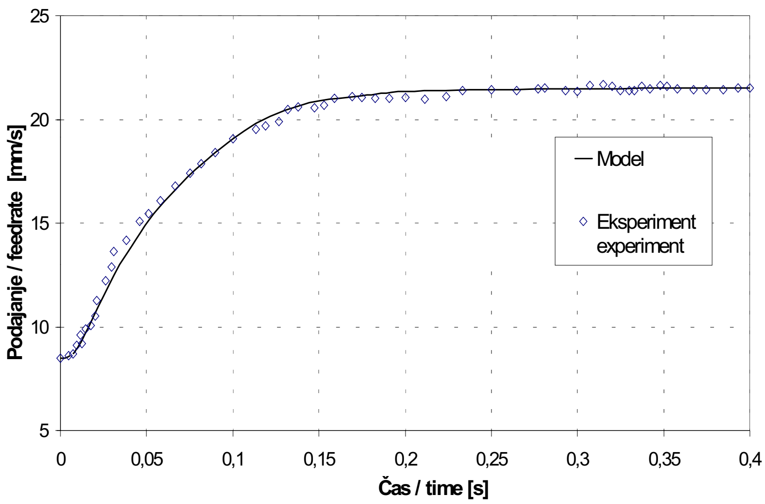
Sl. 3. *Simulator RNK frezanja*
Fig. 3. *CNC milling simulator*

lastno frekvenco 3 Hz in odzivnim časom 0,4 s. Na sliki 4 je podana primerjava preizkusnih in simulacijskih rezultatov za skočno spremembo hitrosti od 7 na 22 mm/s.

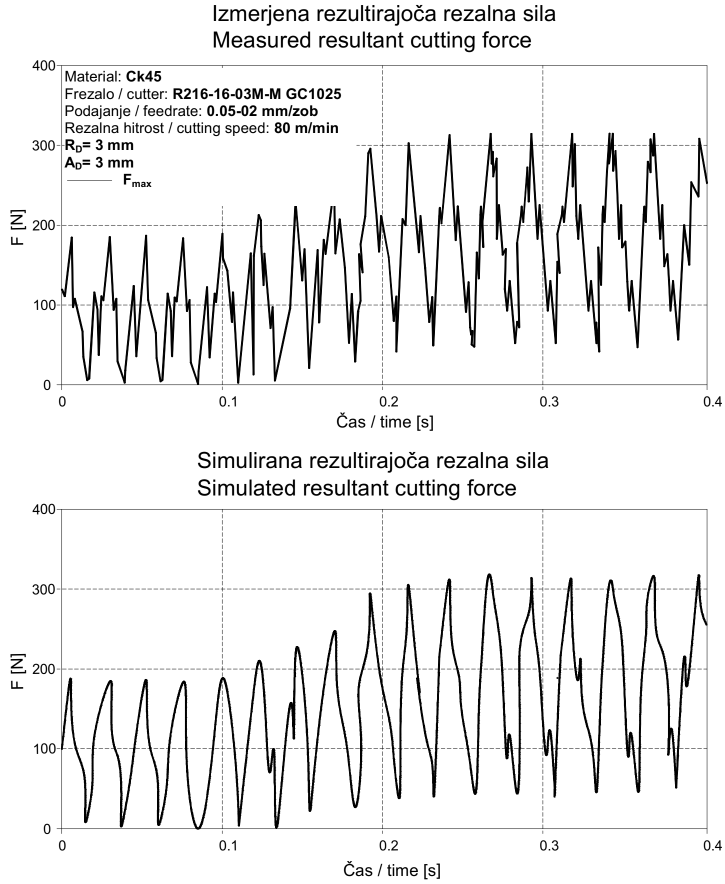
Kombinacija modela podajalnega servopogona, nevronskega modela sil in modela elastičnosti sestavlja simulator RNK frezanja. Vhod v simulator je želeno podajanje, izhod pa rezultirajoča rezalna sila *X*, *Y*. Geometrijska oblika reza je definirana v nevronskem modelu sil. Simulator je potrjen s primerjanjem preizkusnih in simulacijskih rezultatov. Za potrditev smo izvedli vrsto rezov s spremenljivim

system with a natural frequency of 3 Hz and a settling time of 0.4sec. A comparison of the experimental and simulation results for a velocity step change from 7mm/sec to 22mm/sec is shown in Figure 4.

The feed-drive model, the neural force model and the elasticity model are combined to form the CNC milling simulator. The simulator input is the desired feedrate, and the output is the *X, Y* resultant cutting force. The cut geometry is defined in the neural force model. The simulator is verified by a comparison of the experimental and model simulation results. A variety of cuts with feedrate changes



Sl. 4. *Primerjava dejanskega in simuliranega podajanja*
Fig. 4. *Comparison of actual and simulated feedrate*



Sl. 5. *Primerjava simulirane in izmerjene rezalne sile*
Fig. 5. *Comparison of simulated and measured cutting force*

podajanjem. Na sliki 5 je prikazana izmerjena in simulirana rezultirajoča sila pri skočni spremembi podajanja iz 0,05 na 2 mm/zob. Eksperimentalni rezultati se dobro ujemajo z rezultati modelov tako za povprečne sile kakor tudi za največje sile. Do očitnih neskladnosti je lahko prišlo zaradi nenatančnosti nevronskega modela sil in nemodelirane dinamike sistema.

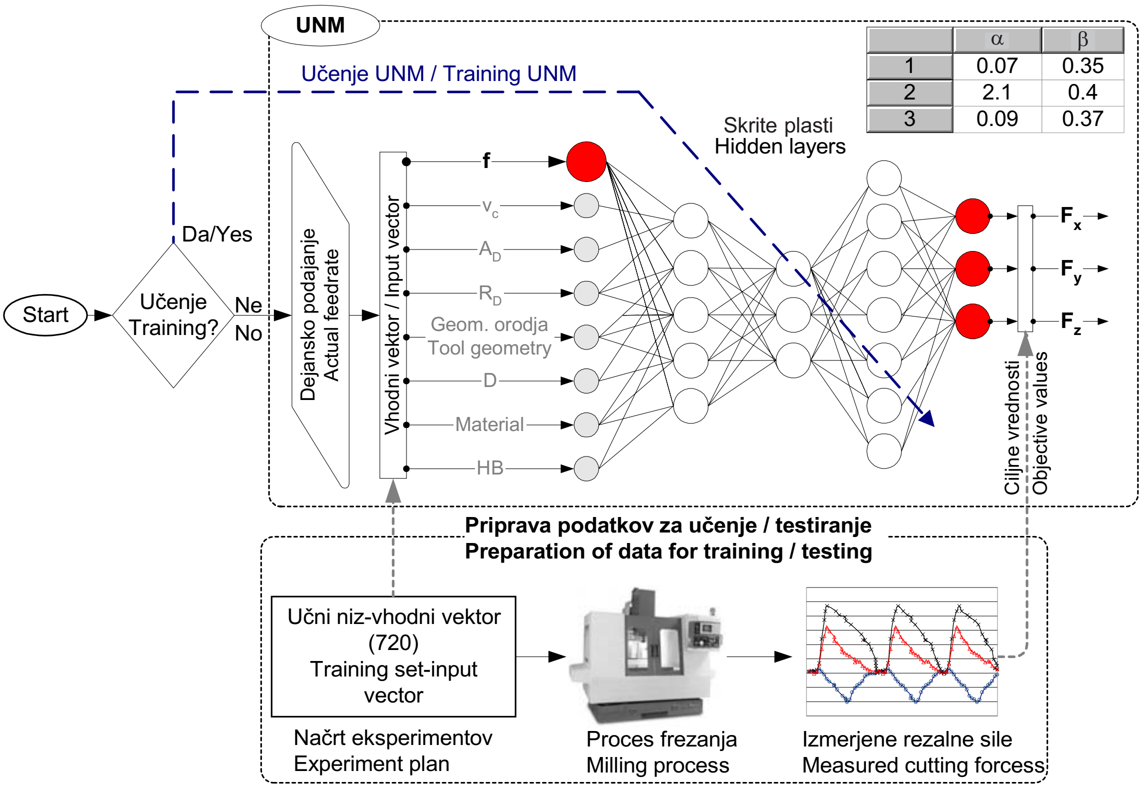
3.1 Simulator dinamike odrezovanja

Za izvedbo sprotnega modeliranja postopka odrezovanja, je predlagana standardno BP nevronska mreža (UNM), ki temelji na dobro znanem učnem pravilu vzvratnega širjenja napake. Pri predhodnih preizkusih se je izkazalo, da je zmožna izvleči model dinamike sil neposredno iz podatkov preizkusov. Namenjena je za simulacijo dinamike postopka. UNM za modeliranje potrebuje osem vhodnih nevronov: za podajanje (*f*), rezalno hitrost (v_c), prečno in

were made for the validation. The measured and simulated resultant force for a step change in the feedrate from 0.05mm/tooth to 2 mm/tooth is presented in Figure 5. The experimental results correlate well with the model results in terms of average and peak force. The obvious discrepancy might be due to inaccuracies in the neural force model and the unmodelled system dynamics.

3.1 Simulator of the Cutting Dynamics

To realise the on-line modelling of the cutting process, a standard BP neural network (UNM) is used, based on the popular back-propagation learning rule. During preliminary experiments it proved to be sufficiently capable of extracting the force dynamics model directly from the experimental machining data. It is used to simulate the dynamics of the cutting process. The UNM for modelling needs eight input neurons: for federate (*f*), cutting speed



Sl. 6. *Topologija modela za napovedovanje rezalnih sil*
Fig. 6. *Predictive cutting-force model topology*

vzdolžno globino reza (A_D/R_D), vrsto obdelovanega materiala, trdoto obdelovanega materiala, premer frezala (D) in geometrijsko obliko orodja. UNM beleži vhodne podatke samo v numerični obliki, zato je treba podatke o geometrijski obliki orodja in materialu spremeniti v numerično kodo. Geometrijska oblika frezala je nakazana z osemštevilčno sistematizacijsko kodo, ki vsebuje podatke o obliki rezalnega roba, cepilnem kotu, prostem kotu, polmeru konice, osnovnem materialu, oplaščenju ploščice in dolžini rezalnega roba. Izhod iz UNM so komponente rezalne sile, zato so potrebni trije izhodni nevroni. Za poenostavitev simulatorja frezanja se priredi UNM tako, da med napovedovanjem prezre vse parametre vhodnega vektorja razen podajanja. Večina parametrov vhodnega vektorja se namreč med simulacijo ne spreminja (npr. premer in geometrijska oblika frezala, material itn.).

Podrobna topologija uporabljene UNM z optimalnimi učnimi parametri je podana na sliki 6. Optimalna UNM vsebuje 5, 3 in 7 nevronov v skritih nivojih.

(v_c), radial and axial depth of cut (A_D/R_D), type of machined material, hardness of the machined material, cutting-tool diameter (D), and tool geometry. The ANN registers the input data only in numerical form; therefore, the information about the tool, the cutting geometry and the material must be transformed into a numerical code. The geometry of the cutter is indicated with an 8-digit systematization code containing data on the cutting-edge shape, the rake angle, the free angle, the tip radius, the base material, the cutting coating and the length of the cutting edge. The outputs from the UNM are the cutting force components, and so three output neurons are necessary. For simplification of the milling simulator the neural network is so adapted that during prediction it overlooks all the input parameters except feeding. During the simulation most of the input vector parameters do not change (e.g., cutter diameter and geometry, material etc.).

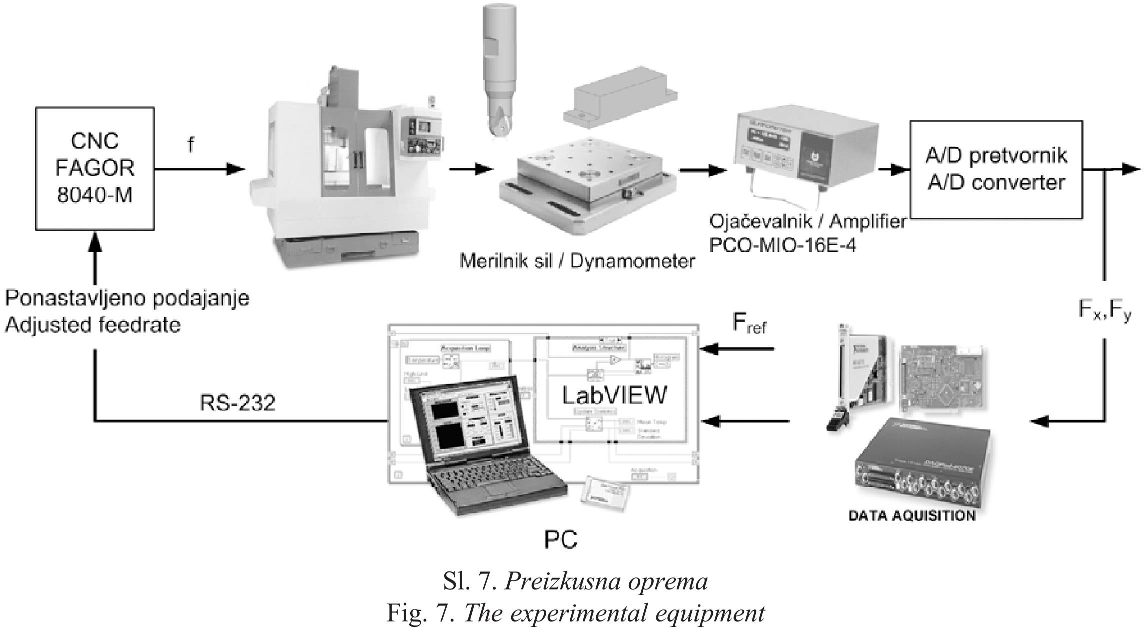
A detailed topology of the used NN with optimal training parameters is shown in Figure 6. The optimal UNM configuration contains 5, 3 and 7 neurons in hidden layers.

4 SISTEM ZA ZBIRANJE PODATKOV IN PREIZKUSNA OPREMA

Slika 7 prikazuje opremo za zbiranje podatkov, ki sestoji iz dinamometra, vpenjalne priprave in programskega modula. Rezalne sile so izmerjene s piezoelektričnim dinamometrom (Kistler 9255), nameščenim med obdelovancem in mizo stroja. Med obdelavo se rezalna sila prenese na dinamometer prek obdelovanca. Piezoelektrični kremen v dinamometru bo obremenjen in nastal bo električni naboj. Električni naboj se nato prenese na večkanalni nabojni ojačevalnik prek priključnega kabla. Nato večkanalni nabojni ojačevalnik ojača naboj (Kistler 5019A). V nabojnem ojačevalniku je mogoče nastaviti različne parametre, tako da dobimo zahtevano ločljivost. Na izhodu ojačevalnika se bo električna napetost ujemala s silo glede na nastavljene parametre nabojnega ojačevalnika. Modul vmesnikove strojne opreme je sestavljen iz povezovalnega bloka, modula za obdelavo analognega signala in 16-kanalnega analogno-digitalnega pretvornika A/D (PC-MIO-16E-4). V pretvorniku A/D bo analogni signal spremenjen v digitalni signal, tako da programska oprema LabVIEW lahko sprejme in prebere podatke. S programom LabVIEW so nato električne napetosti spremenjene v komponente sil *X*, *Y* in *Z*. S tem programom je mogoče hkrati pridobiti tri komponente sile in jih prikazati na zaslonu za nadaljnje analize. Za obdelavo izberemo oblikovno frezalo z izmenljivimi

4 DATA-ACQUISITION SYSTEM AND EXPERIMENTAL EQUIPMENT

The data-acquisition equipment consists of a dynamometer, a fixture and a software module, as shown in Figure 7. The cutting forces were measured with a piezoelectric dynamometer (Kistler 9255) mounted between the workpiece and the machining table. When the tool is cutting the workpiece, the force is applied to the dynamometer through the workpiece. The piezoelectric quartz in the dynamometer will be strained and an electric charge will be generated. The electric charge is then transmitted to the multi-channel charge amplifier through the connecting cable. The charge is then amplified using a multi-channel charge amplifier (Kistler 5019A). In the charge amplifier, different parameters can be adjusted so that the required resolution can be achieved. Essentially, at the output of the amplifier, the voltage will correspond to the force depending on the parameters set in the charge amplifier. The interface hardware module consists of a connecting plan block, analogue signal conditioning modules and a 16-channel A/D interface board (PC-MIO-16E-4). In the A/D board, the analogue signal will be transformed into a digital signal so that the LabVIEW software is able to read and receive the data. The voltages are then converted into forces in *X*, *Y* and *Z* directions using the LabVIEW program. With this program, the three axial force components can be obtained simultaneously, and can be displayed on the screen for further analysis. The ball-end milling cutter with interchangeable cutting inserts of type R216-16B20-040 with



Sl. 7. *Preizkusna oprema*
Fig. 7. *The experimental equipment*

rezalnimi ploščicami tipa R216-16B20-040 z dvema rezalnima roboma, premera 16 mm in s kotom vijačnice 10°. Izbrali smo rezalno ploščico R216-16 03 M-M s cepilnim kotom 12°. Material rezalne ploščic je P10-20 oplaščen s TiC/TiN, z oznako GC 1025. Komunikacija med sistemom krmiljenja in krmiljem NK stroja je izvedena prek RS-232 protokola. Spremenljivka popravka podajanja DNCFRO je na voljo sitemu vodenja s frekvenco 1 kHz.

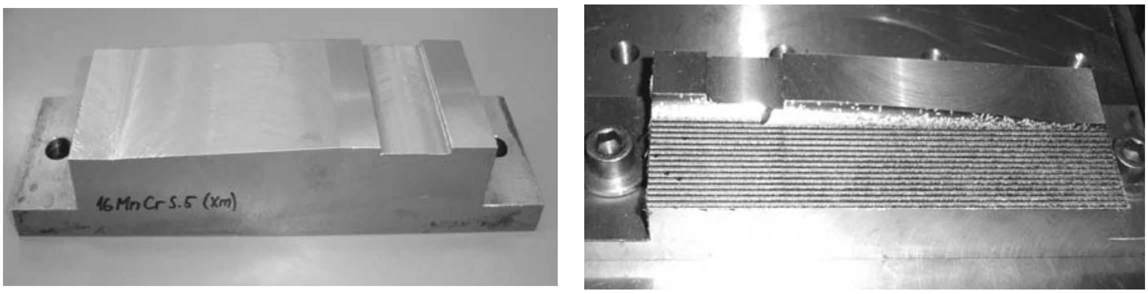
5 PREIZKUSNO TESTIRANJE KOMBINIRANEGA PRILAGODNEGA SISTEMA KRMILJENJA

Da bi preverili stabilnost in robustnost predlagane strategije krmiljenja, sistem najprej analiziramo s simulacijami na LabVIEW-ovem simulatorju Simulink [12]. Nato sistem testiramo z dvema preizkusoma na RNK frezalnem stroju (tipa HELLER BEA1) za jeklena obdelovanca Ck 45 in 16MnCrSi5 XM pri variabilni vzdolžni globini reza. (Preizkus 1- prizmatični obdelovanec; preizkus 2- obdelovanec z nepravilnim profilom, glej sliki 8, 9). Vrednosti podajanja za vsak rez se najprej določi z

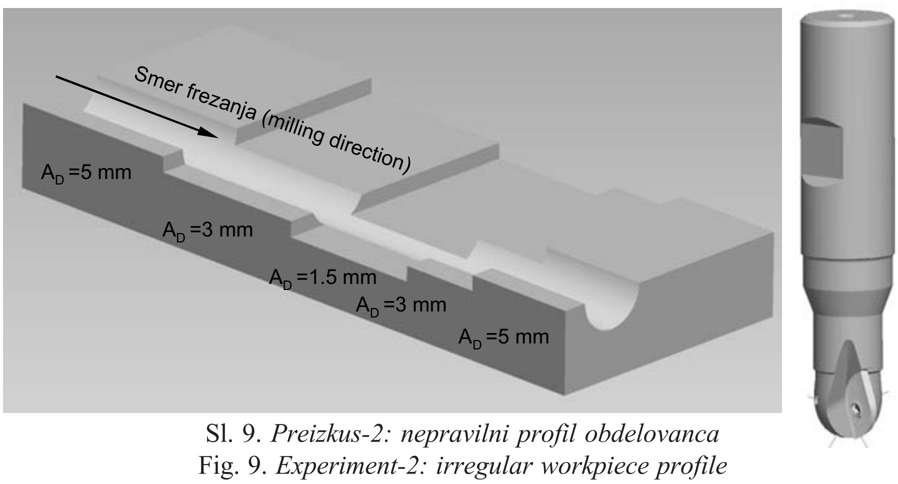
two cutting edges of 16 mm diameter and a 10° helix angle was selected for machining. The cutting inserts R216-16 03 M-M with a 12° rake angle were selected. The cutting insert material is P10-20 coated with TiC/TiN, designated GC 1025. Communication between the control system and the CNC machine controller is via the RS-232 protocol. The feedrate override percentage variable DNCFRO is available to the control system at a frequency of 1 kHz.

5 EXPERIMENTAL TESTING OF THE COMBINED ADAPTIVE CONTROL SYSTEM

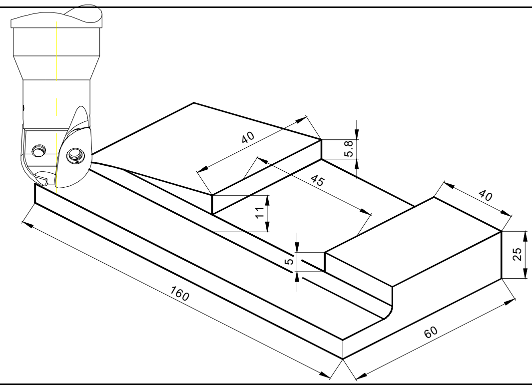
To examine the stability and robustness of the proposed control strategy, the system is first analysed by simulations using LabVIEW´s simulation package Simulink [12]. Then the system is verified by two experiments on a CNC milling machine (type HELLER BEA1) for Ck 45 and 16MnCrSi5 XM steel workpieces with a variation of the axial cutting depth (Experiment 1- prismatic workpiece; experiment 2- workpiece with irregular profile, see Figure 8, 9). The feed rates for each cut are first optimized off-

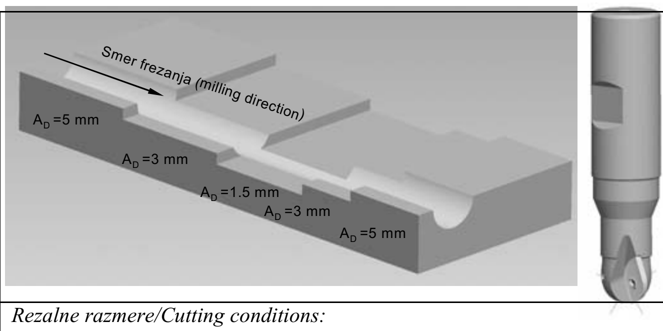


Sl. 8. *Preizkus-1: prizmatični obdelovanec*
Fig. 8. *Experiment-1: prismatic workpiece*



Sl. 9. *Preizkus-2: nepravilni profil obdelovanca*
Fig. 9. *Experiment-2: irregular workpiece profile*

a)	
Preizkus 1/Experiment 1: Prizmatični obdelovanec/ Prismatic Workpiece	
Test_A (Stalno podajanje / Constant feedrate)	*Rezalne razmere/Cutting conditions:* Podajanje/Feedrate: 0,08 mm/zob / 0.08 mm/tooth Rezalna hitrost /Cutting speed: *v*=80 m/min Predprogramirana vzdolžna globina reza / Pre-programed axial depth of cut A_D=2 mm Prečna globina reza R_D =4mm F_{ref}=280 N Rezultat /Result: Slika/Figure: 11a
Test_B (Predlagani kombinirani sistem krmiljenja / Proposed combined control system)	Startno podajanje/Starting feedrate: 0,08mm/zob / 0.08 mm/tooth Dopustno nastavljivo območje/Allowable adjusting rate 0,08-0,2 mm/zob / 0.08-0.2 mm/tooth Rezalna hitrost/Cutting speed: *v*=80 m/min Vzdolžna globina reza / Axial depth of cut A_D=2-8 mm Prečna globina reza R_D =4 mm F_{ref}=280 N Rezultat /Result: Slika / Figure: 11b

b)	
Preizkus 2/Experiment 2: Nepravilni profil obdelovanca / Irregular workpiece profile	
Test_A (Stalno podajanje / Constant feedrate)	*Rezalne razmere/Cutting conditions:* Podajanje/Feedrate: 3 mm/s Vrtljaji vretena / Spindle speed: 2400 min^{-1} Vzdolžna globina reza / Axial depth of cut A_D=2 -5 mm Prečna globina reza R_D =16 mm F_{ref}=650 N
Test_B (Predlagani kombinirani sistem krmiljenja / Proposed combined control system)	Startno podajanje / Starting Feedrate: 2,5 mm/s Dopustno nastavljivo območje podajanja /Allowable adjusting rate of federate: 2,5-11 mm/s Vrtljaji vretena / Spindle speed: 2400 min^{-1} Vzdolžna globina reza / Axial depth of cut A_D=2 -5 mm Prečna globina reza R_D =16 mm F_{ref}=650 N Rezultat /Result: Slika / Figure: 12

Sl. 10. *Načrt preizkusov: a)rezalne razmere za prizmatični obdelovanec, b) rezalne razmere za nepravilni profil obdelovanca*

Fig. 10. *Plan of experiments: a) cutting conditions for prismatic workpiece, b) cutting conditions for irregular workpiece profile.*

ločeno optimizacijo, nato se izvede obdelava s prilagodnim krmiljenjem.

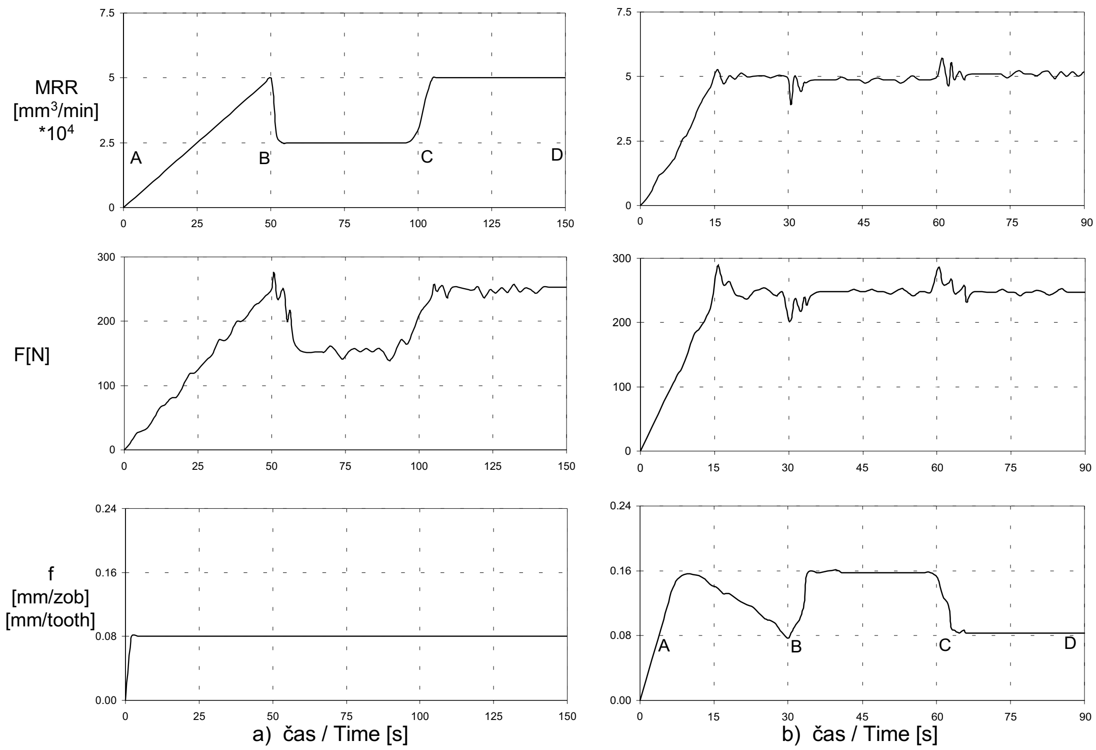
Izvedli smo dve glavni seriji preizkusov, pri katerih smo obdelali dva obdelovanca različnih profilov. Podrobni preizkusni pogoji in izmere obdelovanca so prikazani na sliki 10. Prvi test je klasično odrezovanje s stalnim podajanjem (Test_A). V drugem testu smo predlagani kombinirani sistem uporabili pri frezanju, da bi dokazali njegovo učinkovitost (Test_B).

Za preizkuse izberemo oblikovno frezalo (R216-16B20-040) z dvema rezalnima robovoma, premera 16 mm in s kotom vijačnice 10°. Rezalne razmere so: širina frezanja R_D=3 mm, startna globina frezanja A_D=2 mm in rezalna hitrost v_c=80 m/min. Pri prilagodnem krmiljenju uporabimo enake parametre kakor pri preizkusih pri klasičnem frezanju. Da bi z zgradbo kombiniranega sistema na sliki 1 optimirali vrednost podajanja, izberemo želeno rezalno silo (F_{ref}=280 N), predprogramirano podajanje 0,08 mm/zob in njegovo dopustno nastavljivo območje (0 - 150%).

line, and then machining runs are made with a controller action.

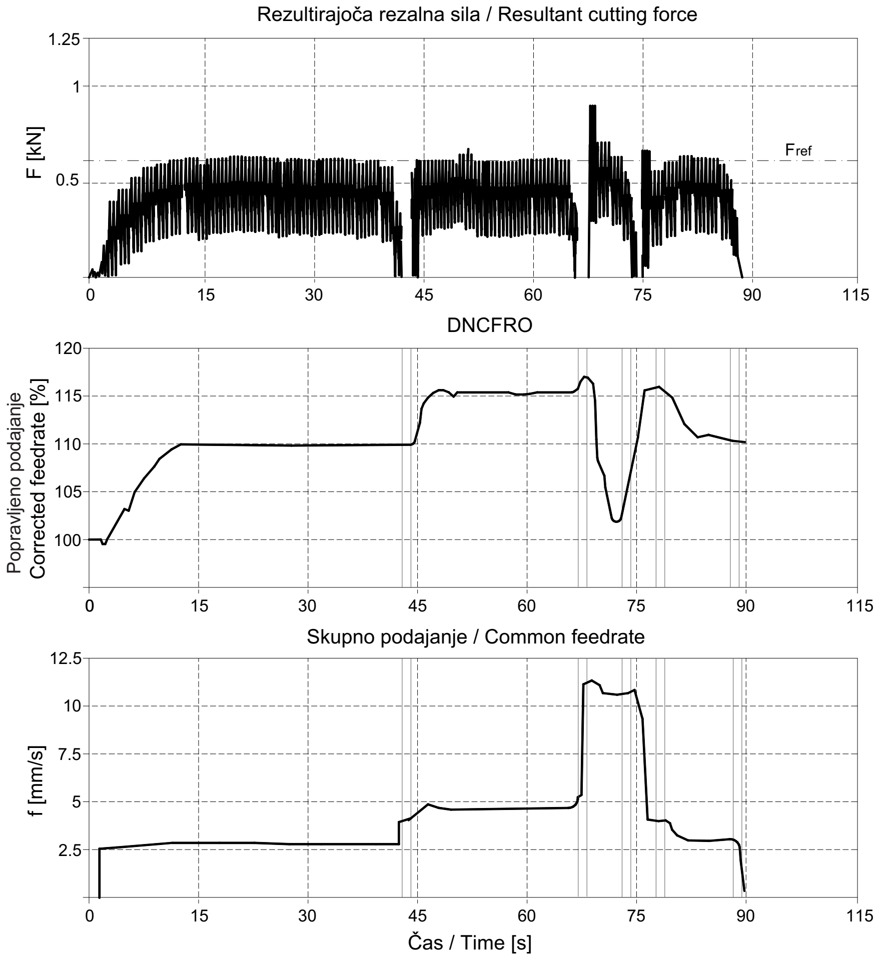
We conducted two main series of tests, in which two differently shaped workpieces were machined. The details of the experimental conditions and the dimensions of the workpiece are shown in Fig. 10. The first test is conventional cutting with a constant feedrate (Test_A). In the second test, the proposed combined system was applied during milling to demonstrate its performance (Test_B).

The ball-end milling cutter (R216-16B20-040) with two cutting edges of 16 mm diameter and a 10° helix angle was selected for the experiments. The cutting conditions are as follows: milling width R_D=4 mm, starting milling depth A_D=2 mm and cutting speed v_c=80 m/min. The parameters for adaptive control are the same as for the experiments in conventional milling. To use the structure of the combined system in Figure 1 and to optimise the feedrate, the desired cutting force is (F_{ref} =280 N), the pre-programmed feed is 0.08 mm/teeth and its allowable adjusting rate is (0–150%).



Sl. 11. *Preizkus-1: odziv MRR, rezultirajoče rezalne sile in podajanja, a) klasično frezanje-Test_A, b) frezanje s predlaganim sistemom prilagodnega krmiljenja-Test_B*

Fig. 11. *Experiment-1: response of MRR, resulting cutting force and feedrate, a) Conventional milling-Test_A, b) Milling with proposed adaptive control system-Test_B*



Sl. 12. *Preizkus-2: obdelava nepravilnega profila z ločenim optimiranjem rezalnih pogojev in prilagodnim nastavljanjem podajanja*

Fig. 12. *Experiment-2: machining of irregular profile by off-line optimizing of the cutting conditions and adaptive adjusting of the feedrate*

Na sliki 11 so prikazani odziv MRR, rezalne sile in podajanja, pri spremenljivi globini rezanja (preizkus-1). Slika prikazuje rezultate preizkusa, pri katerem se s sprotnim nastavljanjem podajanja ohranja največjo rezalno silo na ravni želene vrednosti.

Drugi preizkus je obdelava nepravilnega profila obdelovanca (sl. 9), ki jo sestavlja pet ravnih rezov z različnimi vzdolžnimi in prečnimi globinami. Ta preizkus prikazuje zmožnost prilagodnega sistema za vzdrževanje stalne rezalne sile med odrezovanjem. Želena rezalna sila je 650 N. Čas vzorčenja je 20 ms in hitrost zajemanja je 28,8 kHz. Slika 12 podaja rezultate drugega preizkusa, pri katerem uporabimo optimirane vrednosti podajanja in UNKS.

Figure 11 is the response of the cutting force and the feedrate when the cutting depth is changed (Experiment-1). It shows the experimental result where the feedrate is adjusted on-line to maintain the maximum cutting force at the desired value.

The second experiment is machining of an irregular workpiece (Fig. 9) consisting of five straight cuts with different axial and radial depths of cut. This experiment demonstrates the ability of the adaptive system to maintain a constant cutting force during machining. The desired cutting force is 650N. The sample time is 20ms and the scanning rate is 28.8 kHz. The results of the second experiment using optimized feedrates and UNKS are presented in Figure 12.

6 REZULTATI IN RAZPRAVA

V prvem preizkusu s stalnim podajanjem (Test_A - slika 11a) doseže MRR največjo vrednost šele v zadnjem odseku obdelave. Medtem ko v drugem preizkusu (sl. 11b) obdelujemo isti obdelovanec s prilagodnim krmiljenjem, pri katerem se povprečna dosežena vrednost MRR bolj približa največji vrednosti. Če primerjamo sliki 11a in 11b, vidimo, da se rezalna sila pri sistemu frezanja z nevronskim krmiljenjem ohranja v bližini vrednosti 650 N in je podajanje od točke C do D skoraj identično kakor pri klasičnim frezanju. Od točke A do točke C je vrednost podajanja pri prilagodnem sistemu frezanja višja kakor pri klasičnem RNK sistemu, zato se učinkovitost prilagodnega frezanja izboljša. Rezultati preizkusov kažejo, da je mogoče MRR izboljšati za 27 odstotkov. Izvedena je časovna analiza obdelave za klasično in za prilagodno frezanje. S prilagodnim sistemom krmiljenja dosežemo v enem rezu 40-odstotni časovni prihranek. Za celotno obdelavo je potrebnih 15 rezov; s tem skrajšamo obdelavo zelo preprostega obdelovanca za 15 minut.

Drugi preizkus z majhnimi in velikimi skočnimi spremembami izvedemo zato, da testiramo stabilnost sistema v širokem območju rezalnih razmer. Sistem ostane stabilen pri vseh preizkusih, z le majhnimi odstopanji lastnosti. V drugem preizkusu UNKS s povečevanjem podajanja ohranja največje sile na ravni vrednosti 650 N. Počasnejši odziv nevronske krmilne sheme je opažen le na začetku reza ena in tri.

Lastnosti kombiniranega sistema so ocenjene s tremi parametri: čas obdelave, absolutna vrednost največje rezalne sile in normalizirana standardna napaka Nsn:

6 RESULTS AND DISCUSSION

In the first experiment using constant feedrates (Test_A-Figure 11a) the MRR reaches its proper value only in the last section. However, in the second test (Figure 11b), machining the same piece but using adaptive control, the average MRR achieved is much closer to the maximum MRR. Comparing Fig. 11a to Fig. 11b, the cutting force for the neural control milling system is maintained at about 650N, and the feedrate of the adaptive milling system is close to that of the conventional milling from point C to point D. From point A to point C the feedrate of the adaptive milling system is higher than for the classical CNC system, so the milling efficiency of the adaptive milling is improved. The experimental results show that the MRR can be improved by 27%. A time analysis for the conventional and adaptive control systems has been curried out. With the adaptive control system a time saving of 40% with one cut was achieved. The complete machining requires 15 cuts; thus the machining of a simple workpiece is shortened by about 15 minutes.

The second experiment with small and large step changes is run to test the system stability over a range of cutting conditions. The system remains stable in all experiments, with little degradation in performance. In the second experiment, the UNKS increases the feedrates to obtain peak forces close to 650N. The slower response of the neural control scheme is noticeable at the beginning of cuts one and three.

The combined system performance for the irregular workpiece is evaluated by the time of cut, the maximum cutting force and the normalized standard error:

$$Nsn = \frac{\sqrt{\frac{\sum_{k=0}^{n}(F(k)-F_{ref})^2}{n-1}}}{F_{ref}} \qquad (2),$$

kjer sta: n - število testov (20), F_{ref} - želena rezalna sila. Zmožnost UNKS za nadzor največje sile številčno izrazimo z normalizirano standardno napako.

Rezultati primerjav za preizkus-2 so podani v preglednici 1.

S prilagodnim sistemom krmiljenja dosežemo v enem rezu 24-odstotni časovni prihranek proti frezanju s stalnim podajanjem. Z uporabo UNKS se konice rezalnih sil pomembno zmanjšajo.

where n is the number of samples (20), and F_{ref} is the desired cutting force. The normalized standard error quantifies the ability of the UNKS to regulate the reference peak force.

The results of the comparison for Experiment 2 are tabulated in Table 1.

With the adaptive control system a time saving of 24% with one cut was achieved in comparison with the constant feedrate. With the use of UNKS the peak forces are reduced significantly.

Preglednica 1. *Primerjava lastnosti krmilnikov pri obdelavi obdelovanca z nepravilnim profilom*
Table 1. *Comparison of controller performance for the machining of a workpiece with an irregular profile*

Nepravilni profil Irregular profile	Normalizirana standardna napaka Normalized Standard Error– *Nsn*	Čas obdelave Time of cut [s]	Čas optimiranja [s] /število iteracij Optimization time [s] /number of iterations	Želena sila Desired Force [kN]	Največja rezalna sila Maximal cutting force [kN]
Običajno frezanje-ločena optimizacija Conventional milling-off-line optimization	0,35	115	0,001/18	0,665	1,4
Delilni krmilnik Divisional controller	0,29	98	0,007/23	0,665	1,25
P krmilnik P-controller	0,2	95	0,006/22	0,665	1,1
Nastavljivi PI krmilnik Adjustable PI-controller	0,19	94	0,006/20	0,665	1,0
MPRKS / MRAC	0,22	92	0,012/34	0,665	0,9
Kombiniran sistem Combined system	**0,18**	**88**	**0,001/18**	**0,665**	**0,91**

Delilni krmilnik ima hiter odziv in ga je najpreprosteje izvesti. Nastavljivi PI krmilnik je nekoliko bolj zapleteno, vendar tudi prikazuje kratke odzivne čase. MPRKS je najbolj zapleten, njegov odzivni čas je znatno daljši (8%). Vsa prilagodna krmilja so zmožna nadzorovati rezalno silo in ostati stabilna prek velikega območja geometrijskih variacij.

Dobljeni rezultati se ujemajo s cilji raziskave, po katerih odstopanje krmiljene rezalne sile ne sme odstopati od primerjalne vrednosti za več ko 10 odstotkov.

V primerjavi z večino znanih sistemov krmiljenja oblikovnega frezanja ima predlagani kombinirani sistem naslednje prednosti: 1. računska zapletenost UNKS se bistveno ne povečuje s zapletenostjo postopka; 2. UNKS ima večjo zmožnost učenja kakor klasično prilagodno krmilje; 3. UNKS ima zmožnost posploševanja; 4. Sistem je neobčutljiv za spremembe geometrijske oblike obdelovanca, geometrijske oblike frezala in materiala obdelovanca; 5. Je stroškovno ugoden in ga je preprosto izdelati; in 6. Ne terja matematičnega modeliranja.

Preizkusni rezultati pokažejo, da ima postopek frezanja z zasnovanim prilagodnim sistemom krmiljenja veliko grobost, stabilnost in je bolj učinkovit kakor z uporabljenimi standardnimi krmilniki.

The divisional controller has a quick response and is the simplest to implement. The adjustable PI controller is slightly more complicated, but also demonstrates a short response time. The MRAC is the most complicated and the response time is considerably longer (8%). All of the parameter adaptive controllers are able to control the peak force and remain stable over a large range of geometric variations.

The results achieved are in accordance with the objectives of the research, according to which the controlled cutting force must not deviate from the desired value by more than 10%.

In comparison to most of the existing end-milling control systems, the proposed combined system has the following advantages: 1. the computational complexity of UNKS does not increase much with the complexity of the process; 2. the learning ability of UNKS is more powerful than that of a conventional adaptive controller; 3. UNKS has a generalisation capability; 4. it is insensitive to changes in the workpiece geometry, the cutter geometry, and the workpiece material; 5. it is cost efficient and easy to implement; and 6. it is mathematically modelling-free.

The experimental results show that the milling process with the designed adaptive controller is highly robust, stable, and also has a higher machining efficiency than standard controllers.

Trenutne raziskave kažejo, da ima nevronska krmilna shema znatne prednosti v primerjavi s klasičnimi krmilniki. Prva prednost je, da lahko učinkovito uporabi več zaznavnih informacij pri načrtovanju in izvajanju dejavnosti krmiljenja kakor industrijski krmilnik. Druga prednost je, da se nevronska krmilna shema hitro odziva na zapletene zaznavne vhode, medtem ko je hitrost izvajanja zahtevnih krmilnih algoritmov pri klasičnem krmilniku mnogo manjša.

7 SKLEP

Na temelju modeliranja postopka rezanja, ločene optimizacije in usmerjene nevronske krmilne sheme (UNKS) je sestavljen kombiniran sistem za ločeno optimiranje in prilagodno nastavljanje rezalnih parametrov. To je sistem prilagodnega krmiljenja, ki z digitalnim nastavljanjem rezalnih parametrov krmili rezalno silo in ohranja stalno hrapavost frezane površine.

Uporabnost metodologije prilagodnega nastavljanja rezalnih parametrov je s preizkusi prikazana in preizkušena na 4-osnem frezalnem RNK stroju Heller. Rezultati preizkusov inteligentnega frezanja s strategijo prilagodnega krmiljenja kažejo, da ima razviti sistem veliko grobost in globalno stabilnost. Preizkusi so potrdili učinkovitost prilagodnega sistema krmiljenja, ki se kaže v izboljšani kakovosti površine in manjši obrabi orodja. V tem prispevku je predlagana zgradba sprotnega določevanja optimalnih rezalnih razmer uporabljena pri oblikovnem frezanju, vendar je očitno, da je sistem mogoče razširiti na druge obdelovalne stroje in jim tako povečati učinkovitost.

Current research has shown that a neural control scheme has important advantages over conventional controllers. The first advantage is that it can efficiently utilize a much larger amount of sensory information in planning and executing a control action than an industrial controller can. The second advantage is that a neural control scheme responds quickly to complex sensory inputs while the executing speed of sophisticated control algorithms in a conventional controller is severely limited.

7 CONCLUSION

On the basis of the cutting process modelling, off-line optimization and feed-forward neural control scheme (UNKS) a combined system for off-line optimization and adaptive adjustment of the cutting parameters has been built. This is an adaptive control system controlling the cutting force and maintaining the constant roughness of the surface being milled by introducing digital adaptation of the cutting parameters.

The applicability of the methodology of adaptive adjustment of the cutting parameters is experimentally demonstrated and tested on a 4-axis Heller CNC milling machine. The results of the intelligent milling experiments with an adaptive control strategy show that the developed system has high robustness and global stability. Experiments have confirmed the efficiency of the adaptive control system, which is reflected in an improved surface quality and decreased tool wear. The proposed architecture for an on-line determination of the optimal cutting conditions is applied to ball-end milling in this paper, but it is obvious that the system can be extended to other machines to improve the cutting efficiency.

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