Open architecture digital servodrive for PMSM/PMLM-based machine-tool table feed-drives

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Abstract: The paper presents the results of research work on the development of a rapid-prototyping test stand for testing: servo control algorithms, trajectory generation, algorithms for increasing overall quality of the feed-drive modules within two axis (X-Y) table of the milling machine. Open architecture interface of the prepared control system lets the potential user test functionality of integration of diagnostic tools within the motion controller – directly, without taking into account communication with top-level CNC system.

Key words: CNC, PMSM, PMLM, feed-drive module, rapid prototyping, component-based modeling

1. Introduction

The paper deals with the results of research work on an algorithm prototyping test stand (testing velocity controllers, position controllers, algorithms of two-axis trajectory generation) which has been constructed as part of a National Centre of Science research project, No. N N502 336936 "Development of the construction and the experimental tests of a mechatronic machine tool feed-drive unit with a drive controlled by an intelligent modular actuator".

It consists of: construction part of a commercially available 3-axis milling machine tool from AVIA FOP polish company, model VC600 (Fig. 1), Bernecker&Rainer's APC620 industrial computer used as a main open architecture CNC controller (i.e. G-code interpreter and trajectory generator), National Instrument's cRIO NI9022 Programmable Automation Controller (for implementation of deterministic digital communication between main CNC controller and two axis servodrive), and dSPACE DS1104 (for position and velocity control implementation) with self-designed power electronics module described here. This test stand, which follows the idea of rapid-prototyping, allows, among other things, to integrate the diagnostic functions of a machining process within the velocity and/or position control algorithm. Figure 1 shows the process to be controlled.

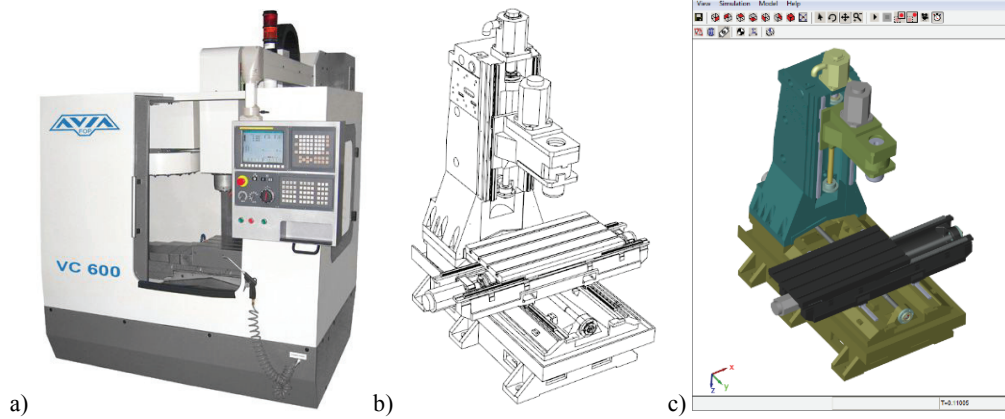a)   b)   c)

Fig. 1. Three-axis machine-tool under investigation; photo of a market available product (a), simplified construction model (b) and STL visualization of SimMechanics multi-body model from Matlab/Simulink (c) Fig.1a. Courtesy: AVIA FOP Warszawa
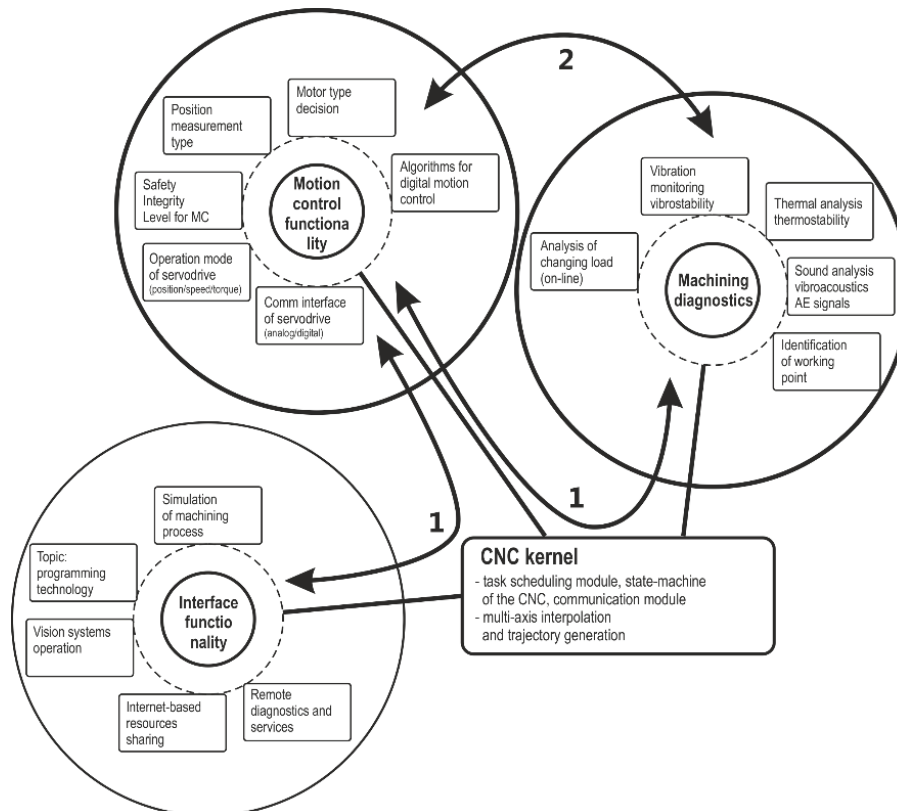

Fig. 2. Integration of machine-tool diagnostic (connection 2) within the motion control functionality vs. typical industry available approach (connection 1)

In the constructed test stand, it is possible to monitor: the temperature of frame elements of a machine tool, vibrations, vibroacustic signals and other signals. It can be also included into the motion control algorithms. Original idea proposed within the presented here project is shown in Figure 2.

Presented test stand enables the potential user (it is under development in other projects) to do research in the following areas:

• vibroacoustic diagnosis of machine tools (among other things, a fusion of vibration and acoustic pressure sensors),
• thermal correction of power screw positioning of a feed unit,
• on-line assessment of the machining quality based on a fusion of measuring signals and the analysis of the surface image of a machining object.

What is the most important from the implementation possibilities, the user's open interface of Matlab/Simulink is maintained. Interfaces are prepared in a way, the final automatically generated code can be implemented in any other than the rather old-fashioned dSPACE DS1104 platform hardware solution. The constructed drive system ensures that the interface is open which allows to implement any diagnostic and/or control functions, both at the level of the main processor and the external control and measurement system.

Moreover, the test stand allows to implement the author's solutions in the field of current control, but it has to be done within the DSP of the power electronics module. Development of the current control algorithms was out of the scope of the project, while in typical industry available solution user almost cannot introduce any changes into this part of servodrive parameters.

2. Dynamic machine tool-workpiece-tool system

The main components of Machine Tool-Workpiece-Tool System [8], with focus on the structure of the applied control subsystem of the drive unit of a machine tool feeding unit, are shown in Figure 3. In the dynamic Machine Tool-Workpiece-Tool System both input and output signals have vector character, whereas the system itself is multidimensional.

The papers [9, 10] deal with the issue of vibrostability of the system in Figure 3 – the stability of machining process, which consists of the following elements: machining process transfer function $\mathbf{W}_{CP}$ delaying unit transfer function $\mathbf{W}_r$, which jointly are to model machining with so-called inner modulation. The following influence the control of a multidimensional dynamic object $\mathbf{W}_{MDS}$: machine cutting force C, friction forces $\mathbf{F}$ taking place in the machine itself and the most essential, from the viewpoint of the present paper, force $\mathbf{M}$ generated by the drive system of feed-drive units. The object is also affected by external disturbances ($\mathbf{Y}$) and/or parameter perturbations of the model.

The equation, which describes how the system in Figure 3 works (in the control pat of feeding unit drives), is presented in the form below:

$$\mathbf{y}_M = col\{\, y_{M,X}, \, y_{M,Y}, \, y_{M,Z}, \,\},$$

$$\mathbf{u} = \{\mathbf{I} + \mathbf{W}_{MDS}[\mathbf{W}_{CP}(\mathbf{I} - \mathbf{W}_\tau) + \mathbf{W}_F + \mathbf{W}_M\mathbf{W}_{Mc}]\}^{-1}\mathbf{W}_{MDS}\mathbf{W}_M\mathbf{W}_{Mc}\mathbf{y}_M + \quad (1)$$

$$+ \{\mathbf{I} + \mathbf{W}_{MDS}[\mathbf{W}_{CP}(\mathbf{I} - \mathbf{W}_\tau) + \mathbf{W}_F + \mathbf{W}_M\mathbf{W}_{Mc}]\}^{-1}\mathbf{Y},$$

where $\mathbf{y}_M$ denotes the position reference value for the feed-drive modules in X, Y, Z axes. Scheme presented in Figure 3 is used within the research work for evaluation of new control algorithms influence on overall quality of the MTWT dynamic system. $\mathbf{W}_{MDS}$ part of MTWT is modelled with the use of well-known rigid multi-body approach. Friction processes transfer functions $\mathbf{W}_F$ were identified during the real-time experiments and the MTWT model had been extended. Motor dynamics $\mathbf{W}_M$ (mechanical part of a model) is taken from data sheets of the motors to be used as well as the electrical part of the motor model introduced into $\mathbf{W}_{Mc}$ transfer functions.
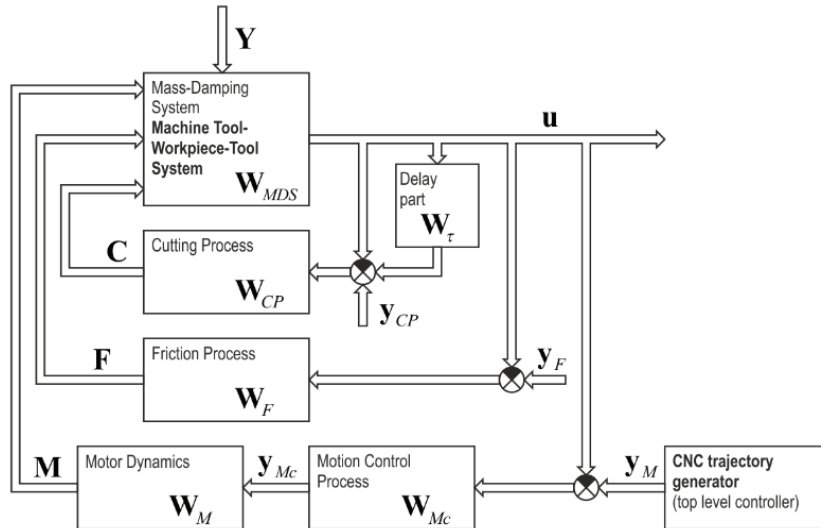

Fig. 3. Dynamic with the motion control taken into account

Typical cascaded motion control architecture for digital PMSM/PMLM servodrives for CNC machines is shown in Figure 4.
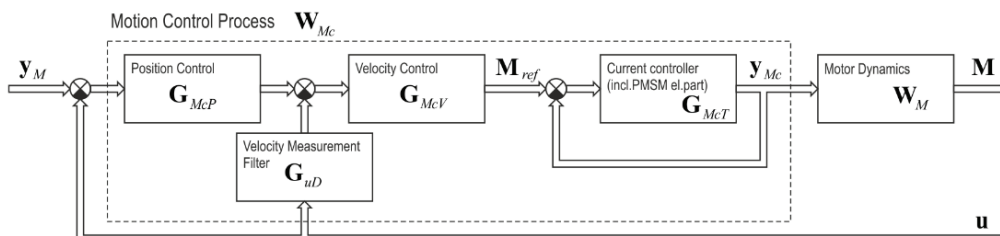

Fig. 4. Typical cascaded structure of the machine tool servo drive

Reference torque from the position/velocity control part of the motion control unit is given by the following equation

$$\mathbf{M}_{ref-casc} = \mathbf{G}_{McV}\left[\mathbf{G}_{McP}(\mathbf{y}_M - \mathbf{u}) - \mathbf{G}_{uD}\mathbf{u}\right],\qquad(2)$$

where $\mathbf{y}_M$, $\mathbf{u}$ are given by the Equation (1). Commissioning of the axis position, velocity controllers in such version of control is quite complicated and typically is supported by the vendor specific motion control parameter tuning software.

Free of typical tuning problems as well as of the position and velocity control dynamics dependency is proposed in the Figure 5 parallel version of position/velocity control.
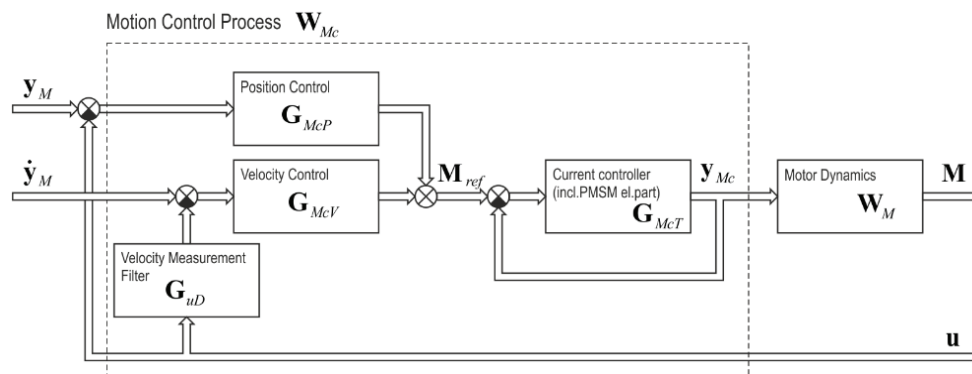

Fig. 5. Proposed parallel structure of the machine tool servo drive

Reference torque from in case of parallel version of machine-tool feed-drive control system:

$$\mathbf{M}_{ref-par} = \mathbf{G}_{McP}(\mathbf{y}_M - \mathbf{u}) + \mathbf{G}_{McV}(\dot{\mathbf{y}}_M - \mathbf{G}_{uD}\mathbf{u}).\qquad(3)$$

Thanks to that approach quality of velocity control (and consequently the overall dynamic stiffness of the feed-drive module) is independent from the position control accuracy. It also simplifies the multi-axis trajectory generation procedures, but it is out of scope of this paper.

3. Robust model-based control for machining purposes

The two-loop Model Following Control (MFC) structure is noted for its simplicity and relatively high robustness to disturbances and stable perturbations. In spite of these advantages, MFC, though being employed is not sufficiently reflected in the literature. The main virtue of the MFC [13] structure is the possibility of acting independently in tracking the reference signal and suppressing effects of disturbances and perturbations. The design team has been conducting the research into MFC based multi-degree-of-freedom robust control.

By the means of machining quality robustness is such system feature that enables constant high quality in the presence of external disturbances and/or unknown but bounded plant parameter changes. Proposition of machining robustness concept is well described by one of the authors in [11].

Ensuring high quality velocity when machining is [5, 12] the key reason for beginning the research into adjusting the model-following control algorithm to the machine tool feed-drive unit control, yet in accordance with a characteristic approach to nonlinear complex object control [1, 11].

Model-based [3] methods introducing inverse model of dynamics are sensitive while machining (cutting) processes as well as friction processes, and due to this fact cannot be used for high speed and high quality control of machine tool feed-drive. Great surveys on the methods for increasing the quality by the means of minimising: tracking, contouring, velocity, acceleration errors in the presence of minimum fluctuation of the control input signal one can find in [4, 14, 16].

Classic cascaded control with the use of PID controllers in single feedback loop local configurations is shown in the Figure 6.
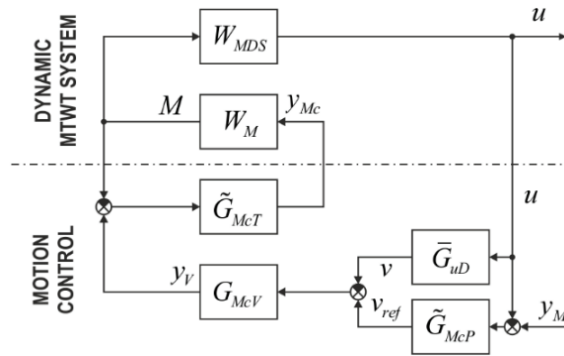
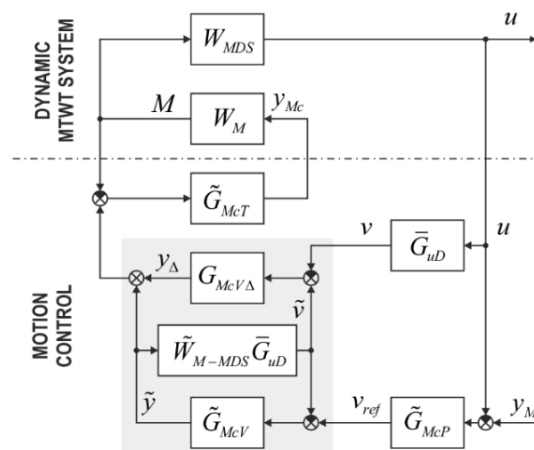

Fig. 6. Classic cascaded position-velocity

Fig. 7. Model-following velocity control

MFC velocity control as discussed in [11] is shown in the Figure 7. Proposed method is free of the inverse kinematic model-based methods.

A modification to the MFC solution has been presented hereunder in the Figure 8. The modification allows to implement an algorithm that improves the quality of velocity control in existing servo drive control systems, as long as they make it possible to send cyclically the additive correction of a set value of current in the *q*-axis to the current controller.
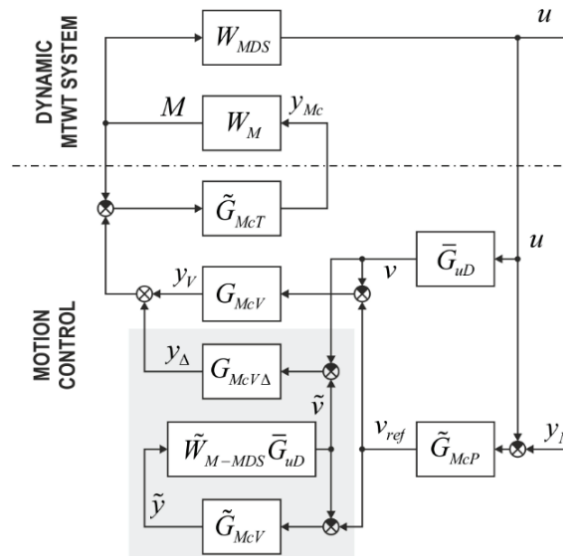

Fig. 8. Model-based correction for velocity control loop

The value of nominal velocity in the system in Figure 8 is calculated on the basis of information about the nominal model of an object, whereas the correction controller "helps" the main controller (which does not need to be modified in any way) to reach the set motion velocity, despite the differences between the model and the controlled object.

By analogy, in the case of the additive current correction one can employ an approach, in which the controller parameters are changed, for instance, in the function of position and/or movement velocity. Both the change of parameters and the additive values of set signals (position, velocity, current) can be realized on the basis of additional measurement information (from temperature sensors, acceleration sensors, vibroacustic sensors).

4. Rapid prototyping of control algorithms

Rapid prototyping as a technique for working out new control algorithms has been known for years and it is used in mechatronic projects, mainly because of shortening the time between preparing a concept and launching final tests [7]. Figure 9 depicts four most popular contemporary design scenarios with the use of rapid prototyping.

Software-in-the-loop part was conducted with the use of the Matlab/Simulink software with the model of process automatically generated from the SolidWorks simplified multi-body construction assembly. Hardware-in-the-loop testing had been conducted in two ways: with the use of B&R CNC computer and with the use of presented here dSPACE solution.

Presently, on the market there are solutions that make it possible to start HIL research (in target equipment) just after finishing simulation tests.

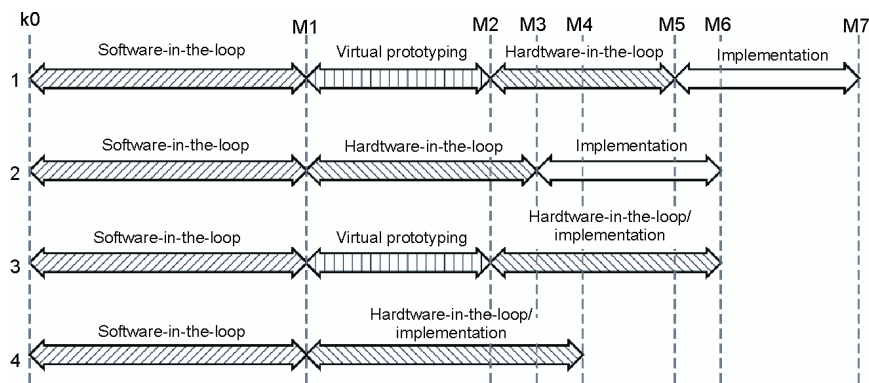The project described here follows scenario 4.

Fig. 9. Mechatronic design scenarios (KO – kick-off, M1 ... M7 – milestones)
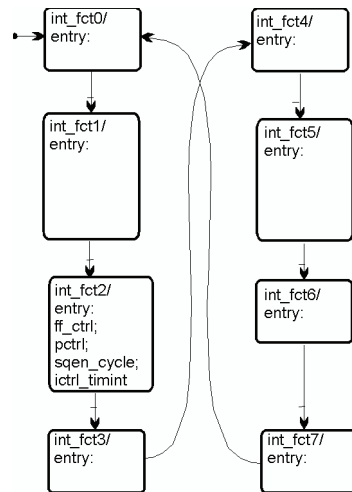

Fig. 10. Stateflow task scheduler of the motion control unit

Prepared code can be simply reused in other control system, i.e. FPGA, ARM controllers, PLC, IPC programmed according to IEC61131. DS1104 platform has a lot of constraints, where the most important is minimal position set point sampling time. Multitasking by the means of different sampling times had to be programmed by hand (with the use of State flow

chart) while in typical IEC compliant industrial control systems it is configured in the Real Time Operating System scheduler, as shown below (with example state given).

Internal requests trigger control subsystems of the reusable dSPACE control code, as shown in Figure 11.
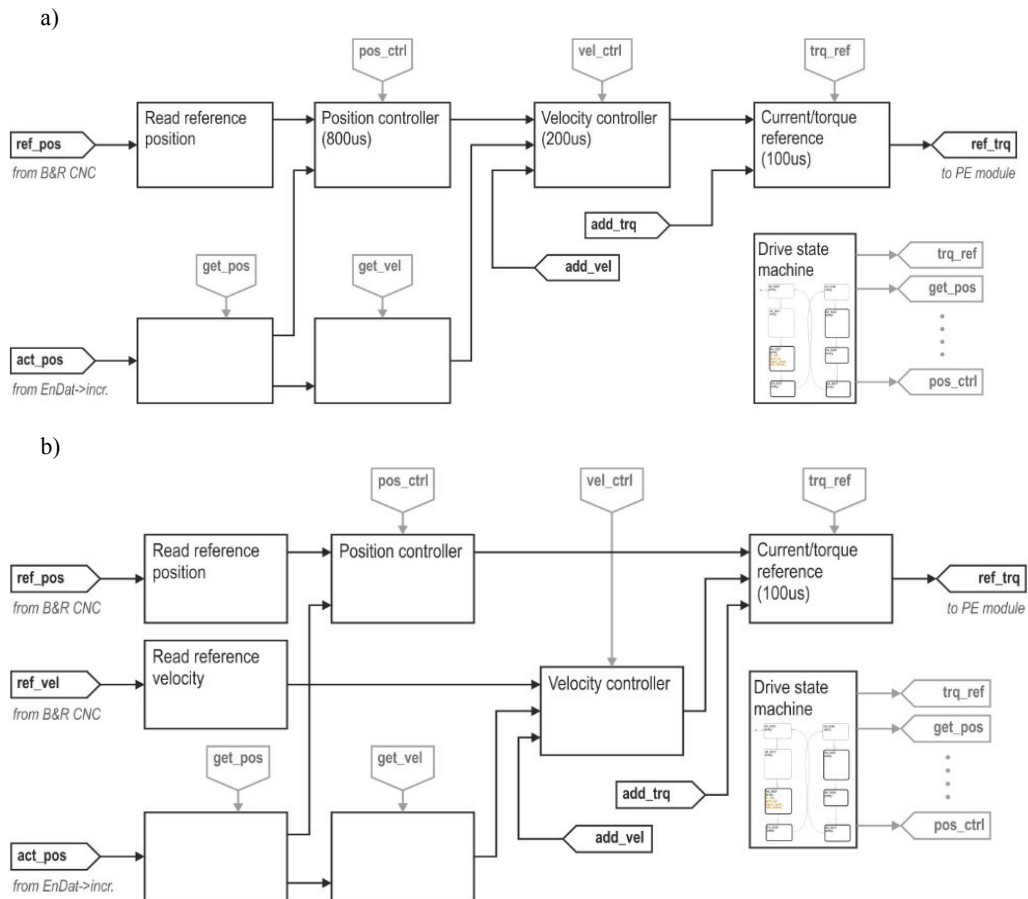
a)

b)

Fig. 11. Control scheme: cascaded (a) and parallel (b) version

As modern industrial control systems can be programmed with the functionality of automatic code generation (i.e. with tools like Simulink PLC Coder) the prepared code is reusable for any future development. It is also compliant with the simplified V-model of the software lifecycle is defined in EN ISO 13849.

5. Prototype test stand

The power supply and control system of feed-drive machine tool table consists of two independently controlled and dedicated inverters, which are powered by a common DC bus

(Fig. 12). Fast transistors have been used as switching keys IGBT (IGW15N120H3), and modern silicon carbide elements have been used as backward diodes (SiC, IDH08S120). The equipment have made it possible to increase the switching frequency of inverters' keys (up to over 20kHz) and to keep a proper level of commutation losses [2]. The efficiency results of one inverter, for selected switching frequencies of the transistors are presented in Figure 13. Decreased generation of EMI disturbances is another advantage of using SiC diodes. Both inverters are powered by a common DC bus. Moreover, they have their own bank of electrolitic capacitors as well as decoupling MKP polipropylene capacitors on every circuit limb of the inverter half bridge.
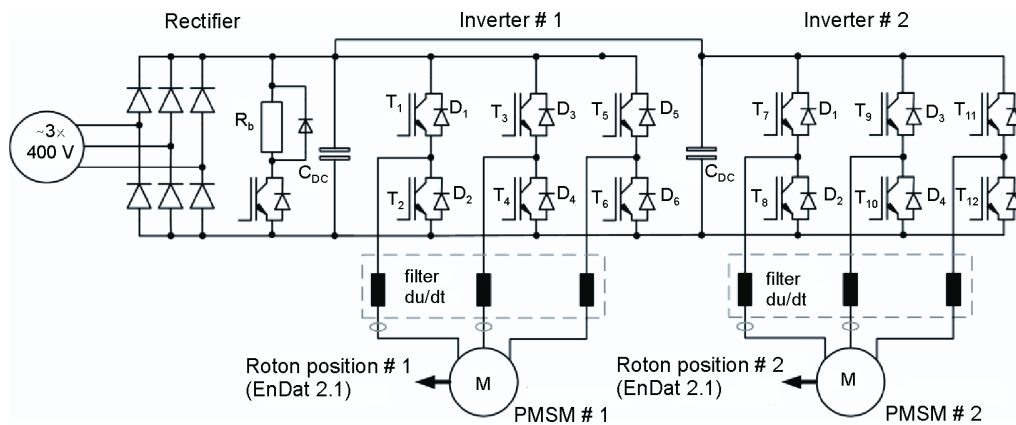

Fig. 12. Supply subsystem of the feed-drive machine tool table

Additionally, to reduce the quantity of emitted disturbances input filters, so called du/dt filters, have been used.
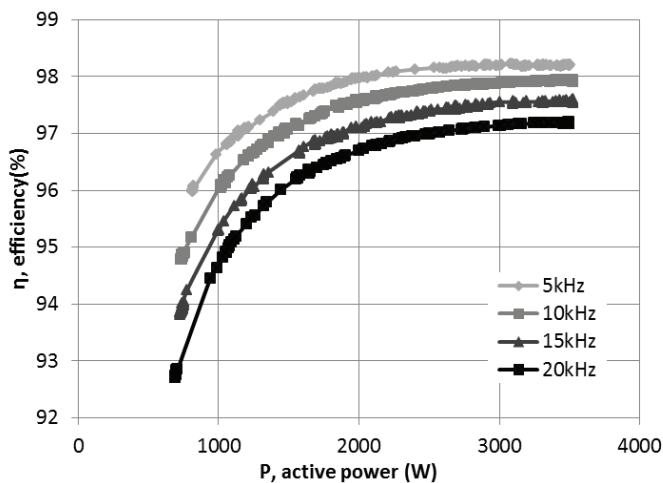

Fig. 13. Result of efficiency measurements of the inverter module

The main control and supervising unit of the two inverters is a high performance floating-point microcontroller of the C2000 family from Texas Instruments: TMS320F28335. Its characteristic features, especially useful in control applications and power processing, are: a substantial number of flexibly configured PWM outputs, high processing speed (CPU 150 MHz clock), CPU with a floating-point architecture, a fast 16-channel and 12-bit A/D converter, inputs for precise measurement of widths of impulses (eCapture), advanced operation emulation and additional protection (Watchdog, emergency situation service – Trip Zone etc.).
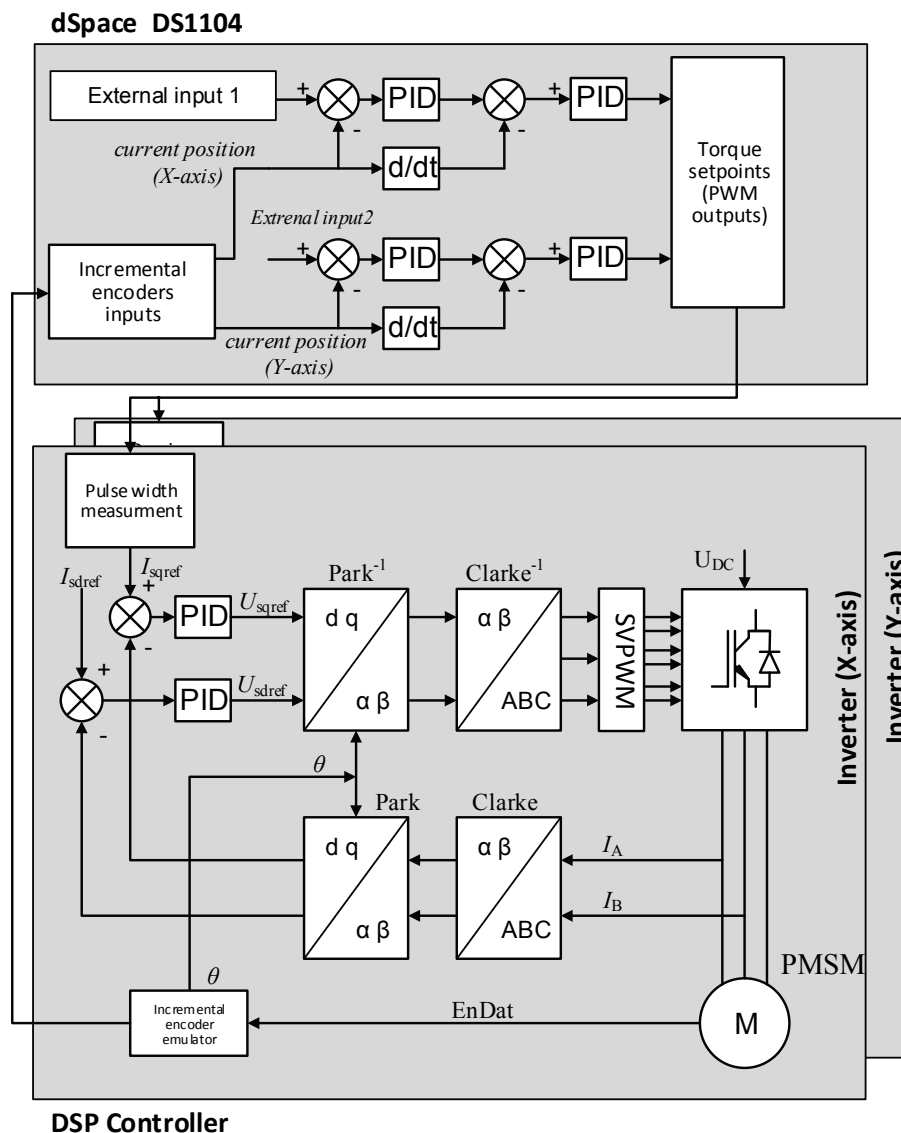

Fig. 14. Functional setup of the test-stand

To send the set value of current (of moment) from superior velocity and position controllers, PWM outputs of a dSPACE controller have been used. eCapture precise pulse duration measurement inputs with a 150MHz sampling rate have been employed as inputs in a DSP controller of inverters. Some innovation is the use of two PWM circuits to set current value for one axis, what allows to increase the precision of the sent information about the required current/moment value (16-bit resolution has been achieved). Nevertheless, it has not notably increased transmission delays in relation to other solutions (for instance, an analogue circuit).

In the solution described, in the machine tool drive frames there are angle converters (encoders) with the EnDat 2.1 (Heidenhain) interface. The installed encoder allows to read 2^{17} (131072) shaft positions within one rotation. Additionally, it is feasible to read the number of rotations performed (maximally 4096). The features make it possible to read the current position of the machine tool table without performing additional "axis homing" activities.

Since it is impossible to read the position in the EnDat standard in the dSPACE DS1104 system, it was necessary to construct an additional independent exchanging system, the purpose of which is to read the encoder's absolute position and to send the piece of information to the dSPACE system. Therefore, in the auxiliary microprocessor system, the following have been implemented: a parallel function of reading two EnDat 2.1 encoders as well as incremental encoder emulation along with a procedure of sending an initial absolute position of an XY table just after starting the system. Implementation of the EnDat to incremental encoder is shown in the Figure below.
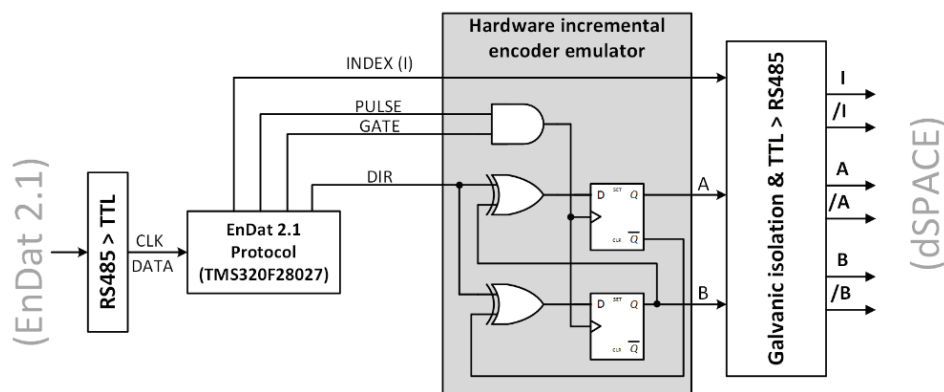

Fig. 15. EnDat absolute multi-turn encoder converter to incremental standard

To make it possible to change internal parameter settings of the inverter, a communication protocol and MATLAB control software have been devised. The software allows to control the inverter operation, to change current controller coefficients in a given algorithm, to configure encoders, to change the settings of current limiting and the like.

The basic assumption of the described subsystem was a possibility of implementing and verifying the operation of various control algorithms. In the testing system, a control algorithm has been implemented for each axis. The control algorithm features direct vector control of

stator current with a constant power angle π/2 [6, 15], the temporary component settings (of transformations and controllers) of which can be registered and modified on-line. It makes it possible to diagnose and analyse the operation of machine tool drives. Figure 15 depicts the test stand consisting of the frame of a numerically controlled machine tool, with the ball-screw driven feed-drive module (here, the object is an X-Y milling machine table).
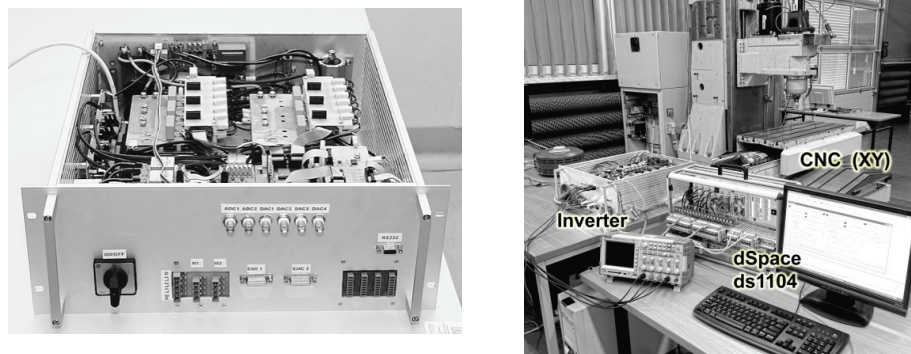

Fig. 16. Power module (left). Test stand (right)

The platform for position/velocity control system within the presented here test stand is a dSPACE DS1104 controller. The main processing unit of the controller is based on a 250 MHz Power PC Texas Instruments processor. Furthermore, the system is equipped with an auxiliary floating-point TMS320F240 processor responsible for more advanced I/O functions, such as PWM signals. The card features analogue-to-digital and digital-to-analogue converters, digital I/O systems, incremental sensors interfaces (counting encoders) as well as standard communication ports (RS232, RS422, RS485). The dSPACE card is equipped with a software interface for Matlab/ Simulink in the form of RTI (Real-Time-Interface) blocks which make it possible to implement and compile a Simulink application and start on a signal processor. Therefore, it is possible to run a real-life simulation. The user's graphic ControlDesk interface allows to freely modify and monitor the parameters of an object which is being tested. Control interface scheme prepared in Matlab/Simulink environment is shown in the Figure 11.

Position reference values on the basis of interpreted the G-coded technological milling programme are transferred from the B&R APC620 CNC main processor (i.e. trajectory generator) to the dSPACE motion controller. Since there is no possibility of direct reference position information exchange between trajectory generator (industrial PC from B&R) and dSPACE controller, it was necessary to exploit auxiliary device – National Instruments PAC controller. The subsequent reference position values which were generated every 800 μs were sent via UDP protocol to NI-9022 controller. The device converted obtained ASCII character data to digital values (Boolean) and sent using FPGA technology and fast digital outputs on dSPACE's digital inputs. Obtained values were interpreted by dSPACE DS1104 controller and converted into scalars.

The procedure for receiving data from is based on periodically reading 16 digital inputs. To synchronize the transmitted data strobe signals are used. The strobe signals depend on the speed of transmission. When the maximum data transmission is set, the changes of sixteen digital inputs are read every 100 μs. This allows to read two 32-bit value in time 400 μs. Which means, that the implemented algorithm allows to set reference trajectory with a frequency of 2.5 kHz.

Presented solution provide high quality, deterministic noise-free communication and allows to efficient data transfer among control algorithm.

8. Verifying the power electronics module operation

To verify the power electronics module operation, a simulation MATLAB/Simulink model has been designed. The model, with an auxiliary dedicated package for modelling power electronic systems and electric machines: Plecs from the Plexim company, makes it possible to simulate chosen working algorithms of the system, to observe basic parameters, to change settings and configuration of controllers and many other things.
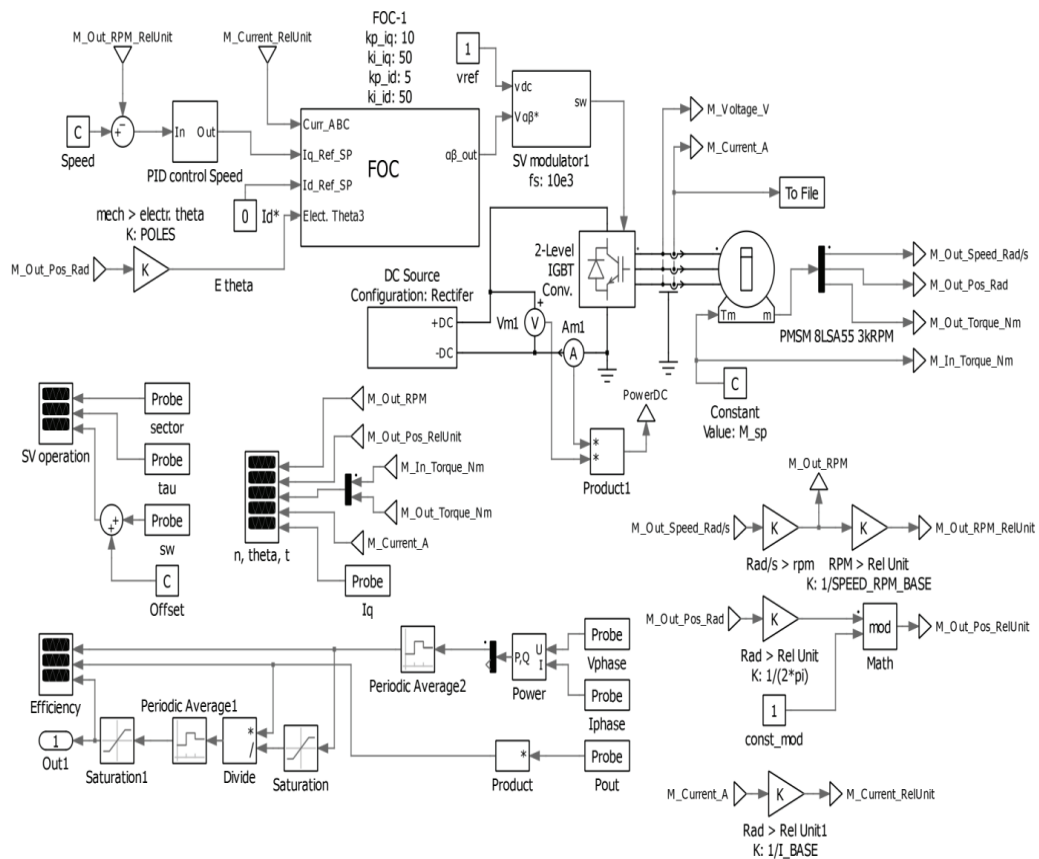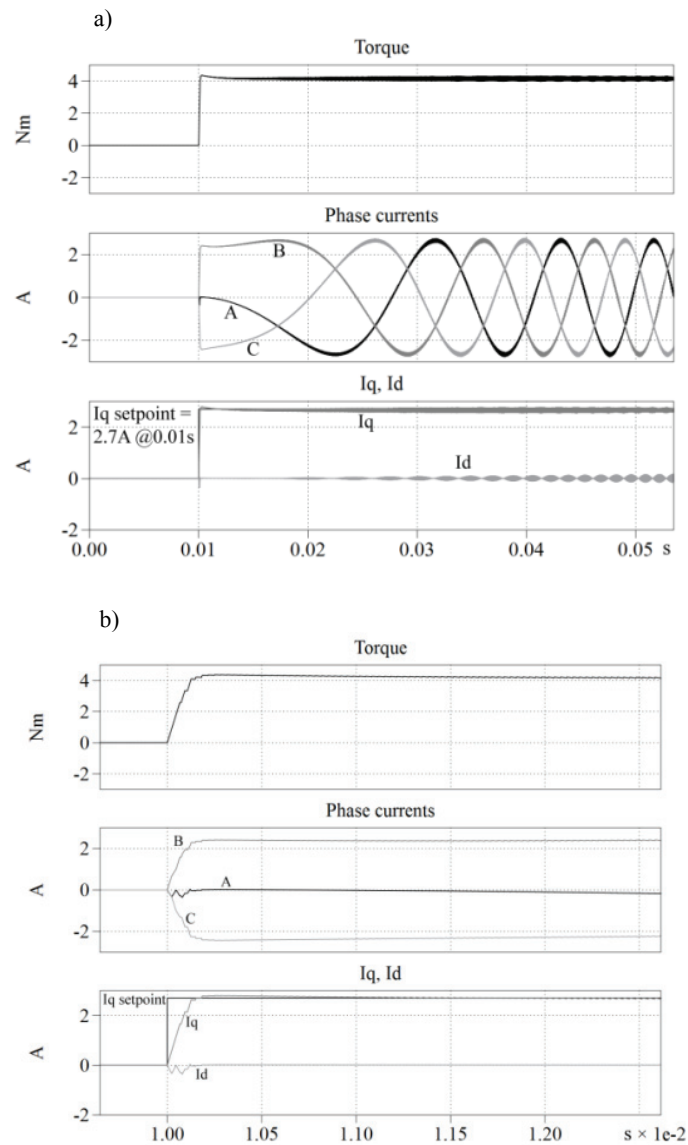

Fig. 17. Program structure in Plecs

a)

b)

Fig. 18. Comparison of simulation (a) and experimental results (b)

10. Conclusions

The aim of the presented test stand for an intelligent servo drive in a Dynamic Machine Tool-Workpiece-Tool System structure was to point out possible ways (available technologically in our times) of improving the geometry and motion quality of new and modernized machine tools.
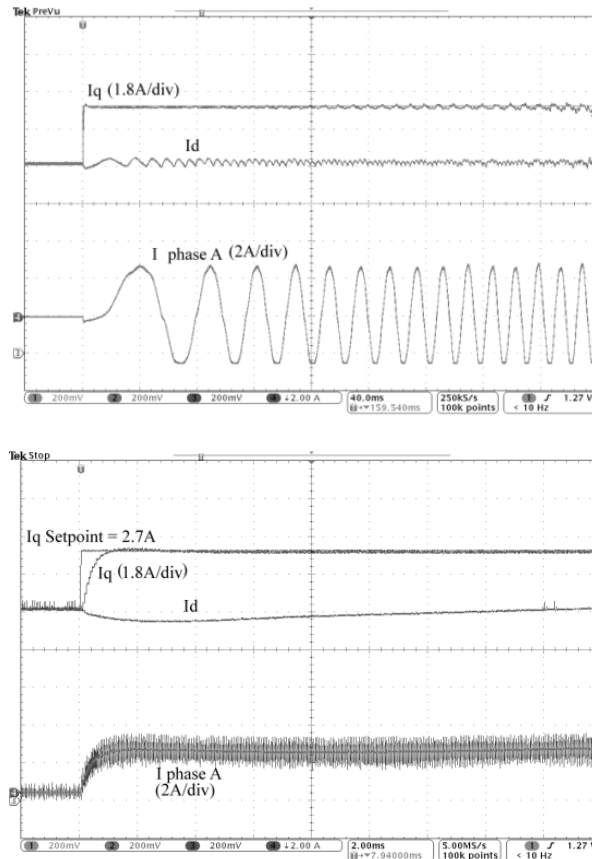
Fig. 19. Recorded results of current

The test stand presented in the paper makes it possible to verify, in a practical way, proposed methods of improving the geometric and motion quality of a machine tool (milling machine) which is numerically controlled at the level of functional open architecture feed-drive system. Due to the solutions applied (absolute measurement of position, integration of vibration measurements), the presented novel is unique in this research area.

While described here project is of high mechatronic value among the modern computer numerical control systems for machine tool, we had to propose integrated condition monitoring solution for robust motion control purposes. This approach is based on the hybrid open architecture which consists of:

- real-time operating functionality (scheduling, multitasking, multithreading) on the top level CNC system;
- hardware computations and Digital Signal Processing for implementation of deterministic real-time communication between;
- highly robust multi-degree of freedom model-based control algorithms (with autonomous and/or controlled switching).

References

[1] *Handbook of hybrid systems control.* Cambridge University Press (2009).

[2] Bonisławski M., Hołub M., *Effects of space vector modulation strategy on hybrid (Si-SiC) inverter losses.* Archives of Electrical Engineering 61(1): 69-75 (2012).

[3] Elfizy A.T., Bone G.M., Elbestawi M.A., *Model-based controller design for machine tool direct feed drives.* International Journal of Machine Tools & Manufacture 44: 465-477 (2004).

[4] Huo F., Poo A.N., *Precision contouring control of machine tools.* International Journal of Advanced Manufacturing Technology 64: 319-333 (2013).

[5] Kosmol J., *Serwonapędy obrabiarek sterowanych numerycznie.* Wydawnictwa Naukowo-Techniczne (1998) (in Polish).

[6] Krishnan R., *Permanent Magnet Synchronous and Brushless DC Motor Drives*. Boca Raton, CRC Press, Taylor and Francis Group, LLC (2010).

[7] Li F., Li D., Huang X., Lai Y., *A Model Driven Methodology for Computer Numerical Control system Design and Development*. IEEE International Conference on Control and Automation, Christchurch, pp. 1465-1470 (2009).

[8] Marchelek K., *Dynamika obrabiarek*. Warszawa: Wyd. Naukowo-Techniczne (1991) (in Polish).

[9] Marchelek K., Pajor M., Powałka B., *Vibrostability of the Milling Process Described by the Time-Variable Parameter Model*. Journal of Vibration and Control 8: 467-479 (2002).

[10] Parus A., Marchelek K., Domek S., Hoffmann M., *Podniesienie wibrostabilności w procesie skrawania z zastosowaniem eliminatora piezoelektrycznego.* Modelowanie inżynierskie 39: 159-170 (2010) (in Polish).

[11] Pietrusewicz K., *Multi-degree of freedom robust control of the CNC X-Y table PMSM-based feed-drive module*. Archives of Electrical Engineering 61(1): 15-31 (2012).

[12] Pritschow G., *On the influence of the velocity gain factor on the path deviation.* CIRP Annals – Manufacturing Technology 45: 367-371 (1996).

[13] Skoczowski S., Domek S., Pietrusewicz K., Broel-Plater B., *A method for improving the robustness of PID control. IEEE Transactions on Industrial Electronics* 52: 1669-1676 (2005).

[14] Yeh S.S., Tsai Z.H., Hsu P.L., *Applications of integrated motion controllers for precise CNC machines.* The International Journal of Advanced Manufacturing Technology 44: 906-920 (2009).

[15] Zawirski K., *Sterowanie silnikiem synchronicznym z magnesami trwałymi*. Poznań: Wydawnictwo Politechniki Poznańskiej (2005) (in Polish).

[16] Zhang L.-B., You Y.-P., Yang X.-F., *A control strategy with motion smoothness and machining precision for multi-axis coordinated motion CNC machine tools.* International Journal of Advanced Manufacturing Technology 64: 335-348 (2013).