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DRIVE DATA ACQUISITION FOR CONTROLLER INTERNAL MONITORING FUNCTIONS

With the current trend of increasing automation, leading to self-organizing machine tools and production machines (“Industry 4.0”), data acquisition and processing becomes more and more important. Based on these data, new monitoring functions and identification methods can be implemented in the machine control. Depending on the algorithms, also drive internal data, such as the actual torque, or the power consumption of the machine axes are required, partially at high sample rates. State of the art computerized numerical controllers (e.g. SIEMENS 840D sl) however, are characterized by a separation of drive system and controller. Drive data, which is not included in the standard bus-connection are difficult to access by the superordinated CNC. The paper addresses this problem, presents and compares various concepts of drive data transfer to a standard industrial CNC/PLC. Subsequently, the most convenient method, which utilizes a drive-internal data recorder is chosen for implementation. It offers flexible drive data acquisition through the PLC at high sample rates, carried out block wise. Experimental results are shown to prove the functionality. Finally, ideas for continuative monitoring and identification methods are discussed.

1. INTRODUCTION

This paper addresses the topic of data acquisition of state of the art machine tool controllers. A current trend in this field is increasing automation along with the need of extensive monitoring functions, which require different sets of data. Contrary to this, typically used Computerized Numerical Controllers (CNC) do not yet offer a sufficient way of data exchange throughout their components and connected devices (see Fig. 1). The goal of this research is to develop/establish a feasible way to access data from the drive system of machine tools with standard hardware, preferably few changes and high flexibility. After the problem formulation with an insight to state of the art numerical controllers and

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bus connection (section 2), the paper presents several methods to record drive data and transfer them to the CNC for further processing in section 3. Subsequently, the implementation and verification of the favoured method is stated in section 4, which forms the basis for superordinated identification and machine monitoring approaches. Thereof, three selected methods, which are currently researched by the authors, are briefly presented in section 5 before a conclusion and an outlook is given.

2. PROBLEM FORMULATION

State of the art computerized numerical controllers typically comprise three separated functional units with different functionality as displayed in Fig. 1 [5],[19]:

- Man-Machine Interface (MMI),
- Numerical Control Kernel (NCK),
- Programmable Logic Control (PLC).

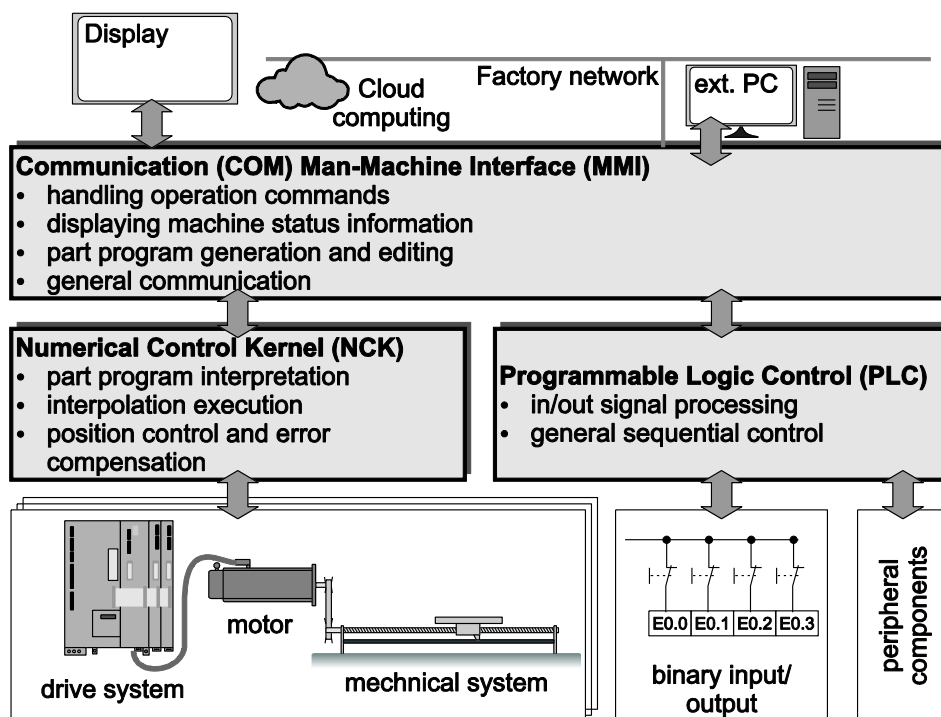


Fig. 1. Functional units of a typical computerized numerical controller [5],[19]

Fig. 1 also shows, how the components interact and how they are connected with peripheral components, drive systems, display devices etc. Taking the three components into account, a permissive possibility of implementing additional functionality for the end-user is given:

- either in the PLC-part or
- on a dedicated computer in the factory network.

Both measures require communication functionality within the CNC-parts and its periphery because required data for the algorithms has to be accessed.

Communication between the three components of the CNC is established and reconfigurable to a certain extend. Data exchange between PLC and NCK, for instance, is realized by a specially reserved memory area (dual-port RAM) [16]. This memory is limited in size but can be read and written by standard methods of programming, either by G-code on CNC-side and established languages (KOP, FUP, AWL) on the PLC-side. Whereas the data exchange between the three controller components is quite feasible, communication between the NCK and the drive is limited to the capabilities of the used drives bus.

Many of European machine tools and their numerical controllers are equipped with the PROFIBUS/PROFINET protocol to exchange data with the drives [11]. Generally, the PROFIBUS is divided into a part of cyclical and acyclical communication (Fig. 2) [3].

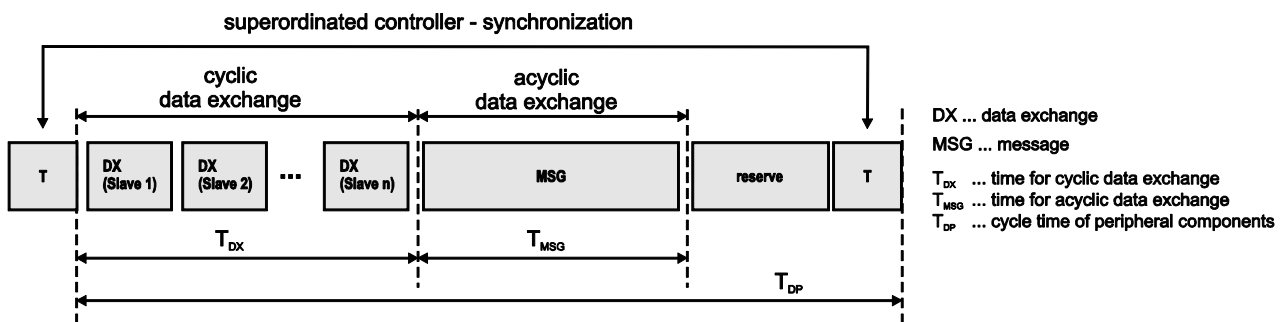


Fig. 2. Structure of one PROFIBUS cycle with cyclical and acyclical part [3]

Data, which is important for axis control, needs to be exchanged in the cyclical part to ensure latest values for each sample. In the standard configuration, values for the setpoint speed and the actual position/actual speed are cyclically exchanged [21].

Table 1. Cyclical data exchange for the PROFIdrive telegram 105 [14]

setpoint transfer from controller to drive		actual value transfer the drive to controller	
name	meaning	name	meaning
STW	control Word	ZSW	status Word
NSOLL	set speed	NIST	actual Speed
M_Red	torque derating	MeldW	message word
XERR	system deviation (for DSC)	e.g. G1_X_IST1	cyclical actual value (incremental encoder)
KPC	position controller gain (for DSC)	e.g. G1_X_IST2	absolute actual value (absolute encoder)

If additional features like the common “Dynamic Servo Control (DSC)” is enabled, the PROFIBUS provides extended data, as presented in Table 1. An overview of common PROFIBUS configurations is given in [14], where also extended telegrams are listed.

They also provide values for torque, current and power, but are not arbitrary configurable by the user. Also a free telegram extension can be parametrized. However, even changing the PROFIBUS telegram itself is complex due to necessary subsequent changes in the hardware configuration, mainly in addresses of the control components. Also data, not included in any of the telegrams could be required. In these cases, advanced methods of drive data acquisition have to be carried out.

3. STRATEGIES FOR DRIVE DATA ACQUISITION

The goal of this section is to present methods for flexible extraction of data from the sensor/actuator level to the field level. Subsequent processing should be possible either on the field level or on the cell level after transfer [8]. Based on the statements from section 2, the main decision is, whether to use the cyclical or acyclical communication section of the PROFIBUS. Furthermore, the following methods focus on the SIEMENS SIMUMERIK 840D controllers with PROFIBUS connection to the SINAMICS drive system, but can also be applied to a connection with PROFINET.

3.1. DATA TRANSFER IN CYCLICAL PROFIBUS SECTION

All presented approaches in this section premise that the required data is included in the PROFIBUS telegram. This has to be realized by choosing the right or extending the PROFIBUS telegram.

A first approach is to access the desired data via PLC. A system function SFC 14 (read consistent data of a DP-normslave, Fig. 3) is provided by the controller manufacturer SIEMENS for this matter [15]. The counterpart for writing operations is the SFC 15. Data is stored on PLC-level in a dedicated data block (DB) which is limited to 32 Byte. Hence, for continuous data acquisition, multiple calls of the SFC 14 with storage in different data blocks are required. The achievable cycle time of reading is limited to the cycle time of the PLC which is ca. 1-10 ms.

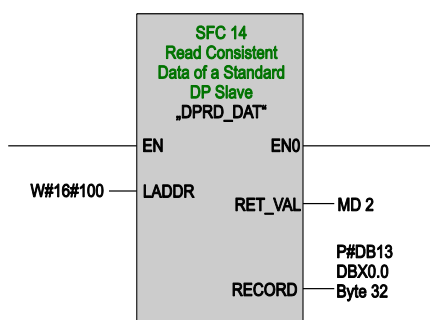


Fig. 3. System function SFC 14 [15]

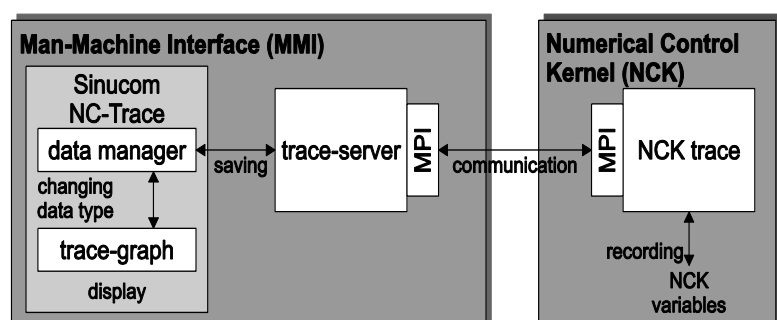


Fig. 4. Schematic view on the NC-trace functionality [17]

A second option is to access drive data via NCK by using synchronized actions [18]. These are user-programmed instructions in G-code, which are executed synchronously to the part program in the cycle time of the NCK. It is possible to record up to 6 variables in the interpolation cycle (IPO cycle). The variable can be chosen arbitrary, but the size of the protocol file, serving as memory, is limited to 50 kByte. If more data is recorded, the oldest values will be overwritten.

A third option is also realizable on the NCK by using the so-called NC-trace [17]. This option is part of the commissioning tool Sinucom NC, which is pre-installed for various diagnosis and commissioning purposes and allows tracing variables/values from the NCK, PLC as well as the MMI. As displayed in Fig. 4, the NCK-trace is located in the NCK and further processes data to the MMI (trace-server). Later on, the interesting values can be displayed and saved via MMI.

3.2. DATA TRANSFER IN ACYCLICAL PROFIBUS SECTION

Contrary to the discussed approaches it is also possible to use the acyclical part of the PROFIBUS connection. Due to a lack of deterministic data exchange, this does not seem to be suitable. However, modern drive systems, like SINAMICS in the considered case, do provide an integrated trace tool. It is located in the control unit, which also realizes velocity and current control. Besides operating by the engineering system, complete control of the trace functionality is also possible through parameter lists [6]. The presented approach uses this way to configure and start data recording as well as reading the recorded values based on list parameters. Those parameters are accessed by the PLC via „RDREC“ (read record, SFB 52) and „WRREC“ (write record, SFB 53) system function blocks (Fig. 5). Main advantages are that basically all parameters of the drive system can be accessed in the comparatively fast cycle time of the drives sample rate (e.g. 125 μ s) without any changes to the cyclic PROFIBUS telegram. The trace function provides two sets of measuring with 8 channels each.

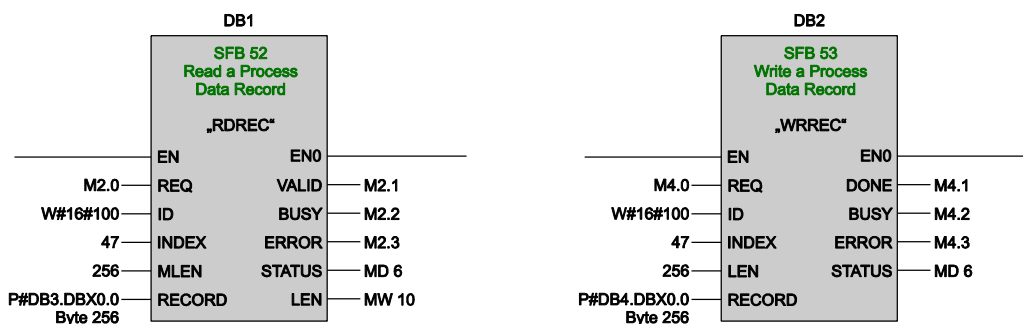


Fig. 5. System functions SFB 52 und SFB 53 [15]

For writing access, a single SFB 53 is required. In this case, the PLC sends a write-demand with parameter number and value to the drive system. Reading access however,

requires SFB 52 and SFB 53. In this case firstly the reading demand has to be sent/written by SFB 53, followed by an answer to SFB 53, delivering the status. Following, the reading access by SFB 52 has to be carried out which will again be confirmed by a status delivery. The flowchart for an entire reading operation is displayed in Fig. 6.

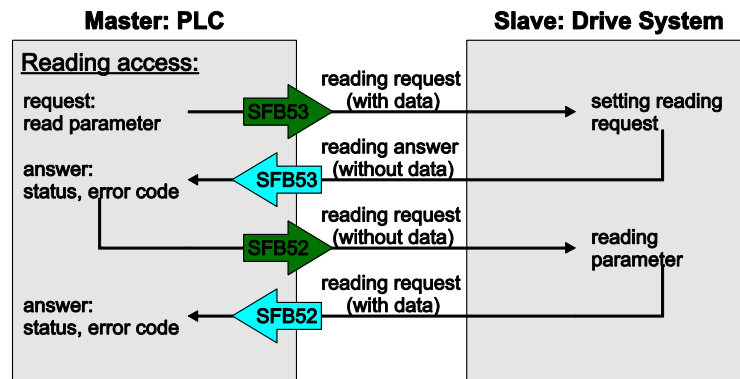


Fig. 6. Schematic flowchart for reading access using SFB 52 and SFB 53

3.3. COMPARISON AND CHOICE OF USED DATA TRANSFER APPROACH

In Table 2, a comparison of the presented approaches is given. The criteria are displayed on the left hand side, whereas achievable performance (cycle time, data size) and necessary effort were focused. Maintenance issues seem to be not as important, because after initial setup all approaches can be started automatically without necessary influence of the end user. Rating of the criteria is supported by color code, where green displays almost no restrictions and red indicates distinct restrictions.

Table 2. Comparison of the presented data transfer approaches

PROFIBUS data exchange	Cyclical part			Acyclical part
critierion	PLC SFC 14	NCK synchronized actions	NCK NC-trace	PLC SFB 52/SFB53
Realizable cycle time	PLC cycle ca. 1-10 ms	IPO-cycle 1 ms	IPO-cycle 1 ms	drive-cycle 125 µs
File size data	32 byte per data block	50 kByte	not directly limited	8192 values
Adaptation effort	high due to necessary PROFIBus telegram adaptation/extension and following operations			low, only adaptation of parameter numbers/addresses
Implementation effort	low	very low	low	medium (multiple calls of SFB)
Required user knowledge	PLC programming, drive commissioning	NC-programming, drive commissioning	drive commissioning	PLC programming

Based on the introduced criteria, Table 2 shows the best overall performance for the variant of acyclical drive data access. Although, data transfer is not very fast via SFB 52/53, low cycle times of data access are possible due to the buffer memory in the drive system. Also the limitation of up to 8192 values is not critical for the intended applications in section 5. Another important advantage of this approach is, that the PROFIBUS configuration and therewith all addresses in the control system can remain unaffected. Hence, for further use, the acyclical drive data access via PLC and SFB 52/53 will be chosen and continuatively explained in the following section. The given higher implementation effort will be tolerated due to the advantages. If other applications with different restrictions are focused, Table 2 provides a guidance to choose the most suitable way of data access.

Main advantages of the chosen approach are:

- sampling rate of the measured signals of down to drive cycle time (125 μ s),
- access to practically all parameters of the drive system,
- no change of PROFIBUS telegram required,
- possibility to use trigger function as simple excitation detection,
- possibility of recording pre-filtered signals,
- easy processing of recorded data to external computer via PLC and Ethernet.

In section 5, possible subordinated applications for the presented method are introduced.

4. IMPLEMENTATION AND VERIFICATION

Expanding the introduced system function blocks towards a data acquisition comprises the three steps *initialization*, *data recording* and *data extraction* (Fig. 7).

In the *initialization* phase, 15 parameters of the trace function have to be set. This includes start/stop, trigger, sample time, duration and the signals to be traced. Configuration of these parameters requires stopping the functionality first. Additional to the parameter number, the address of the drive object (known to the user through commissioning) has to be entered and is transferred into a DWORD by the algorithm. To prevent miss entries and reduce communication time, the procedure is equipped with a plausibility check as well as an automatic adaption to the number of recorded signals.

The second step *data recording* is started by sending the trace configuration. Subsequently, the functionality is started by signal P 4700=1 which either starts data recording immediately or enables the trigger monitoring. Supervision of the status is possible via the dedicated parameter P 4705. Hence, it is cyclically read to recognize the end of recording and subsequently enable data extraction.

In the last step *data extraction* the recorded data, stored in a buffer in the drive system, will be transferred to the PLC. At first, the active trace configuration is read and re-checked with the sent values from step one. Then, recorded values are transferred to the PLC recursively, whereat the data length is automatically adjusted according to the number of traced values. All data is stored on data blocks, corresponding with SFB 52. After all values are transferred, the trace functionality can be restarted with identical configuration,

with new configuration or all parameters can be reset to default. Each of the discussed steps have been implemented to the PLC as a state machine. After:

- the signal adjustment,
- sending the trace configuration and
- receiving the signal “trace finished”

a timer of 500 ms was included to ensure that data buffering is complete. Own experiments showed, that this is necessary when the trace functionality is controlled by the PLC and not by the user which it was intended to. One by one data transfer of two signals with maximum trace length would regularly take up to 160 seconds due to multiple calls of SFB 52/53. By implementing data reading in blocks, this could be reduced to less than 50 s.

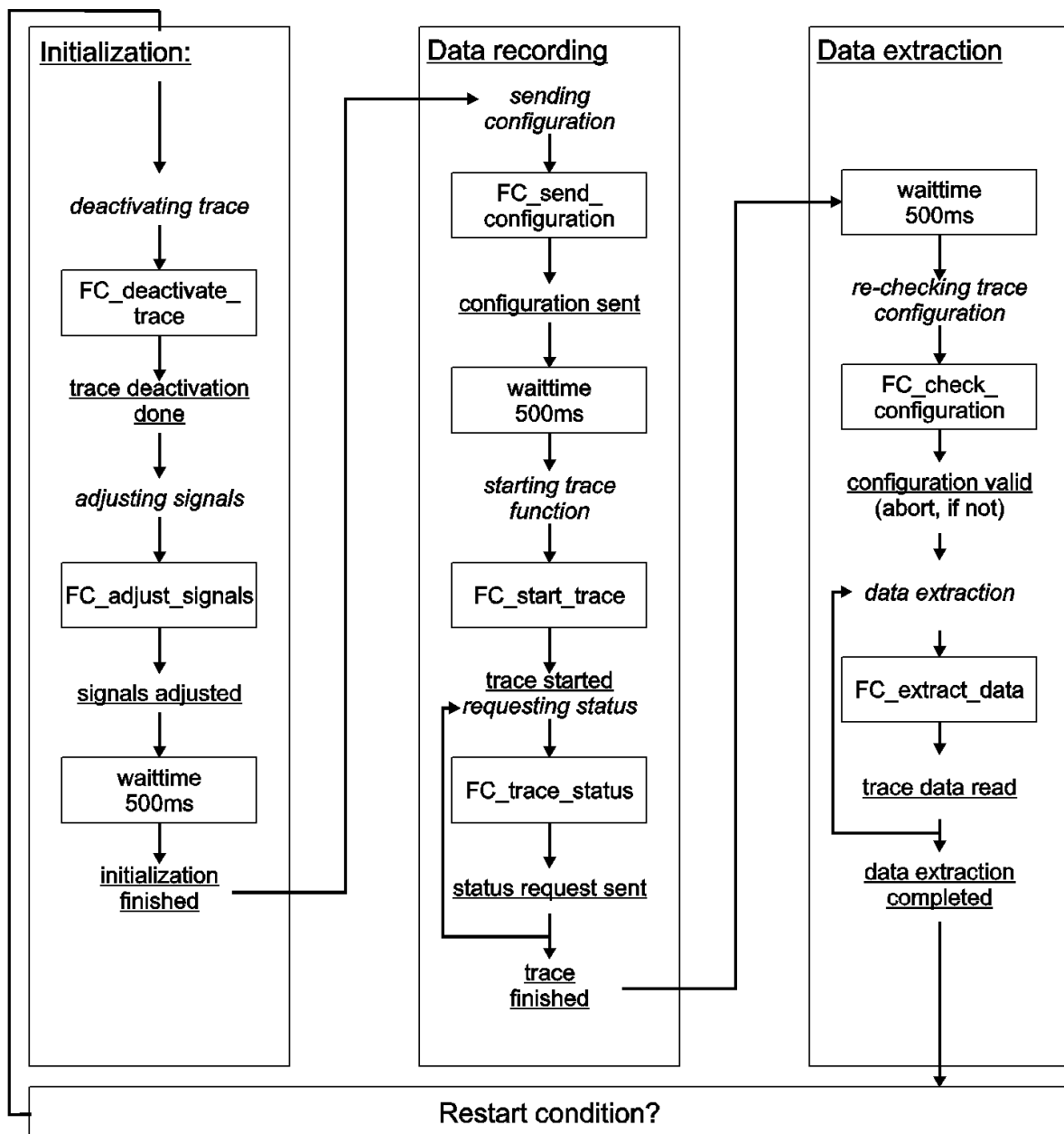


Fig. 7. Schematic flow of the drive data acquisition by three state machines representing three phases

After successfully implementing the algorithm with the introduced phases to the PLC of the numerical controller, several experiments were performed to demonstrate the robustness, accuracy and flexibility of the proposed method.

For a positioning sequence, the drive parameters actual velocity and actual torque were recorded in the drive system and subsequently transferred to the PLC (Fig. 8). The main advantage of the proposed solution is, that data can be accessed in the sample time of the drive system, which is 125 μs in this case.

For monitoring approaches, this advantage balances out the disadvantage which occurs with the comparatively slow data extraction process. A comparison to a manually started trace shows, that the accuracy of data recording is not reduced by the transfer operation. Deviations result from PLC data handling and are less than $5 \cdot 10^{-5}$ 1/min or $5 \cdot 10^{-5}$ Nm respectively. The record duration in this case is 511.875 ms (4096 values).

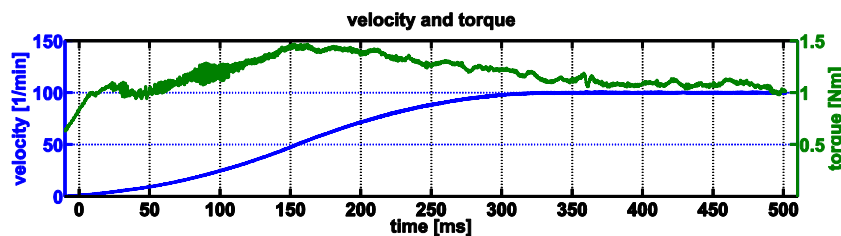


Fig. 8. Recorded values for velocity and torque at 125 μs trace sample time

Some tasks in machine monitoring, however, require different data in different temporal resolutions. The example, displayed in Fig. 9 shows data for temperature and voltage. A significantly higher trace sample time of 100 ms is still sufficient for temperature monitoring purposes. In this use case, the flexibility of the approach concerning the source of data is shown. Via PROFIBUS, these data could only be accessed with high effort.

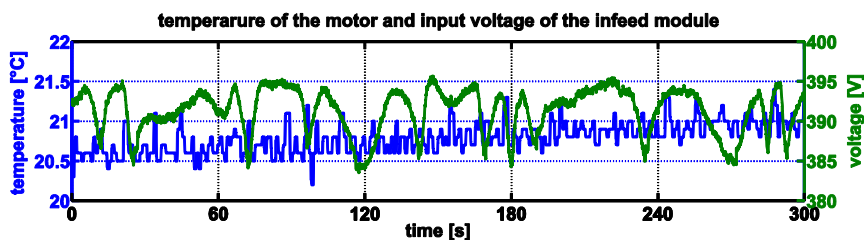


Fig. 9. Recorded values for temperature and voltage at 100 ms trace sample time

5. EXAMPLES FOR SUPERORDINATED IDENTIFICATION AND MONITORING FUNCTIONS

It was already mentioned, that the presented drive data acquisition methods form an important basis for superordinated approaches of identification and monitoring. In the following subsections, three variants, which are particularly important for machine tools and therefore should be implemented in numerical controllers, are introduced.

5.1. PARAMETER IDENTIFICATION DURING REGULAR OPERATION

State of the art system identification approaches do require deterministic test signals, such as step functions, relay-feedback experiments or pseudo random binary signals (PRBS).

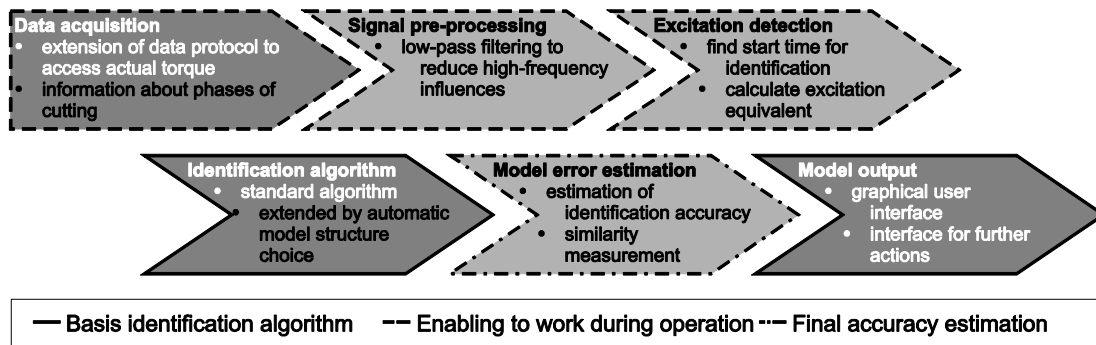


Fig. 10. Necessary extending modules for identification during regular operation

However, if test signals are applied, the process of a machine tool has to be stopped. An alternative approach is, to work with the given axis movements, the so called “natural excitation” of the machine axes [1],[4]. Research shows, that it is possible to identify the total moment of inertia as well as a representative friction model with natural excitation. For this matter, the standard identification method has to be extended. To provide flexibility, the extensions were clustered in modules (see Fig. 10) of which the excitation detection is the most important. When no test signals are used, the recorded signals have to be analysed to extract the most suitable starting and stopping times for identification. This can be done by analyzing the actual torque and actual velocity signal and detecting phases of acceleration or deceleration, based on these signals. Furthermore, the model error is checked by a dedicated module after identification to ensure sufficient model accuracy. Further details to the method can be found in [2]. The required data from the drive system for this approach are segments of torque and velocity (as displayed in Fig. 8), configurations of the control loops, such as e. g. filter frequencies and values of the maximum allowed torque of the motor as well as the moment of inertia of the motor. All of these values can be accessed by the presented data acquisition method.

5.2. PERFORMANCE INDICES

Due to the increasing possibilities of controller internal and drive internal measurement functions, a growing number of monitoring algorithms were developed and published under the term control loop performance monitoring. One attempt is to rate the performance of feedback control with an index, called performance index. Different calculation approaches, focusing on different use cases with varying amount of a-priori knowledge were investigated.

One approach is to set a model based benchmark based on the integral of absolute error (IAE) of the velocity control deviation. The current controller parametrization and its behaviour are rated against a parallel model of controller and controlled system. An order reduced model of the mechanical system (integral plus lag time model, IT_1) is generated as basis for all calculations. For easy commissioning of the performance index, model parameters are not identified in the common way, but re-calculated from the given controller parameters by applying the widely used Symmetrical Optimum [20]. The performance index was investigated with a PI-controller. As visible in Fig. 11, proper tuning is indicated by small values of the performance index. The calculated performance index significantly rises when controller gain and/or integral time are detuned. Further details can be found in [10].

A second way of establishing a performance index is to rate the operant controller setting to a minimum variance based setting. This can also be done for the widely used PI-controller structure [9]. The results show applicability with various attached mechanical systems. Also a good sensitivity to variation of important parameters was proven. Generally, the preferred controller setting (towards minimum variance) is comparatively aggressive (high gain and fast integral time) and therewith not fully applicable to different mechanical systems. However, the sensitivity of the performance index still is suitable for comparison [9]. For these approaches, the velocity control deviation is the main value to be read from the drive system. Additional information, like the operant controller setting is also required and can be accessed.

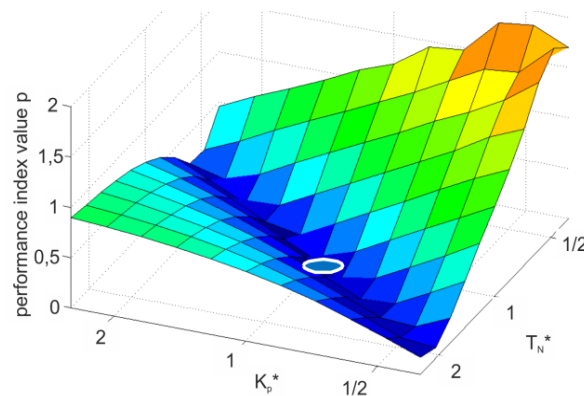


Fig. 11. Performance index results for varying controller settings based on the IAE approach

Furthermore, it is possible to rate the energy consumption, based on the idea of performance indices. For this approach, the command velocity, actual velocity as well as the actual current are required and must be accessed by the presented method of drive data acquisition.

5.3. OSCILLATION DETECTION

Another aspect of control loop performance monitoring is to detect oscillations in various signals of the drive, e.g. axis movements (velocity, torque), which can be caused by aggressively tuned controllers. The Prony method is a parametric approach of spectral

analysis [12]. The achievable resolution is good, even with comparatively short sections of measuring. Hence, a low amount of data is required. Therewith, this approach fits perfectly with the presented data acquisition method. Through achievable low sample times of measuring, also oscillations with high frequency can be detected, which is an advantage to the implementation, presented in [13].

For assessing the performance of drive control, the examined signal (e.g. actual velocity, torque) is remodelled with damped sinusoids (Fig.12). So, the desired information frequency and damping is directly to be evaluated and available for automatic analysis [7], [13]. After application of the method to a test rig, some general advises were derived:

- with a model order of 6, sinusoids approximating the system response show the best results, there is no significant improvement of model fit nor relevant extra information for higher model orders,
- the measurement must only include significant axis movement and the system response, best results were achieved with about 40 samples of measurement,
- different controller settings are correctly rated, especially the critical case of an insufficient damping is properly recognized and
- the performance of two different controller settings resulting in the same damping can be compared trough analysis of frequency and amplitude [7],[13].

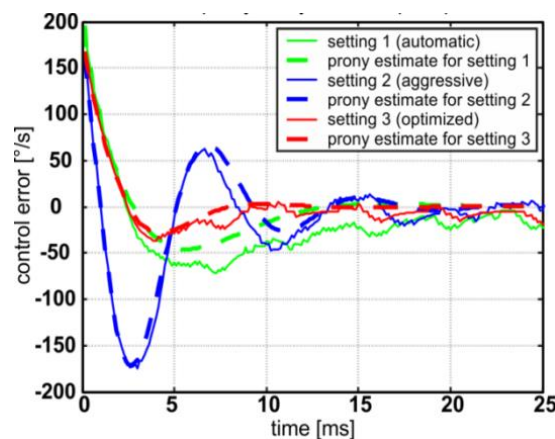


Fig. 12. Recorded system response and damped sinusoids after Prony analysis

With these results, oscillation detection via the Prony method was proven to be also a promising application for constant monitoring of drive systems. All presented approaches in section 5 either require the data acquisition method for their application on CNC-systems or are significantly improved in their range of functions or flexibility.

6. CONCLUSIONS AND OUTLOOK

In the paper, several methods to overcome the problem of non-sufficient data transfer possibilities in industrial numerical controllers were stated. For the intended application of machine monitoring with its specific requirements, the approach to access drive data via the drive internal trace function was chosen due to its flexibility and possibility to record

data in the drive sample time. The duration of data transfer with SFB 52/SFB53 was reduced by block-wise reading operations. The successful implementation of the chosen variant is the essential basis for the application of currently researched monitoring functions, such as identification during operation, oscillation detection and performance indexing.

Continuative tasks in this field will focus on the implementation of data access along with monitoring methods in machine tools. Speeding up the data reading process and connecting the software modules will be specifically important. Further research will show, which machine states can be monitored and which boundaries will arise.

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