Design and Validation of an Adaptive Force Control Algorithm with Parameter Estimation Unit for Electromechanical Feed Axis

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Abstract: Production technology is characterized by the use of electromechanical feed axes, for which the concept of cascade control has become established. The concept is based on linear control engineering. It is not suitable for the control of process forces, which is associated with nonlinearities. Here, adaptive control algorithms from the field of higher control engineering represent a promising approach for improvements of manufacturing strategies and processes in terms of stability, quality, and efficiency. This can also ensure in reducing the number of parts rejected due to bad quality and thus aiding as a significant economic benefit. In this paper, the development of an adaptive control concept that automatically reacts to different and changing environmental conditions during the process is presented. The digital, parameter-adaptive controller consists of a recursive online parameter estimation unit, the controller design procedure, which is based on the setting rule for the symmetric optimum, and the control algorithm. The functionality of the adaptive control concept is demonstrated in simulation and validated by means of experiments on a test setup. It is real-time capable and implemented directly on the machine control together with all calculation algorithms.

1 INTRODUCTION

Currently, production technology is subjected to the influence of global markets more than ever and is forced towards high productivity and economy. A trend towards smaller batch sizes and more individual products is currently being established without compromising on the quality requirements, process reliability, and life cycle costs (Tolio and Urgo, 2013). This leads to new challenges for the industry and hence resulting in promoting the development of flexible and adaptable machines and processes. In modern production machines, mainly electro-mechanical feed axes are used to generate a motion. There are many strategies for controlling machine-specific quantities, such as the position or speed of electromechanical axes. The concept of cascade structure, also known as servo control, has already been established in this field (Leonhard, 2012). However, the performance of this conventional control concept at the machine level has been exhausted. It cannot meet the ongoing efforts to further improve the manufacturing strategies and processes in terms of stability, quality, and efficiency. One possibility for ensuring stable process conditions and reducing rejected parts is closed loop control of quality determining parameters (Allwood et al., 2016). The development of suitable control concepts at the process level, in which significant process variables are taken into account as controlled values, offers considerable scope for improvement at this point. There are many process variables which have an influence to the quality of a part. However, usually it is very difficult to control these values. The metrological acquisition of corresponding parameters constitutes a further challenge.

The process force is a suitable parameter that can be detected well by measurement and provides

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significant economic benefits for many use cases. It is of particular relevance for the majority of processes in the field of production technology and often the limiting factor for the design of the processes and the choice of parameters. Excessive loads can cause damage and defects to the workpiece, tool or machine. In addition, process forces provide important information about the process state and allow conclusions about deviations in the production process (Yao et al., 2013), (Allwood et al., 2016). As a controlled variable, it is predestined to ensure stability and safety of many processes. Direct influence also enables increasing productivity and improving part quality. However, there are many challenges and requirements associated with force control.

The process itself is part of the controlled system, so that deviations of the controlled system and nonlinearities occur more frequently. With classic proportional - integral - derivative (PID) - controllers, this results in poor performance or even instability. PID-control forms the basis of the established cascade control for electromechanical feed axes. The use of higher control concepts is recommended for controlling non-linear systems. But complex control structures and algorithms are difficult to integrate in machine tools with conventional industrial control. Additional hardware usually has to be used for the sensors and control algorithms. The resulting communication times in turn reduce performance and reaction speed is limited. Direct access to the control level is necessary to ensure real-time capability. In this context, measuring the process forces with additional sensors is also problematic. The cycle time is increased even further through signal processing and integration into the control system. Due to the delay times in signal processing, real-time capability is not guaranteed for dynamic movements of feed axes. High-resolution and fast measurement inputs are particularly relevant here. Thus, the design of a suitable control concept with real-time capability represents a significant challenge.

In particular, adaptive algorithms that can react to deviations of the controlled system represent a promising approach to meet the challenges. Adaptive control concepts have been investigated and developed for many tasks in production engineering. A dynamic threshold-based fuzzy adaptive control algorithm for hard-sphere grinding processes was introduced by (Li et al., 2012). (Vrabel et al., 2016) examined an adaptive control system with constraints for a drilling process. (Maher et al., 2015) developed an adaptive neuro-fuzzy inference system, which uses a cutting force signal for the surface roughness prediction in computerized numerical control (CNC) end milling. An online parameter self-adaptive force controller for robot milling was designed in consideration of the robot feed-direction dynamics and the time-varying first-order model of the cutting process by (Xiong et al., 2020). (Deng et al., 2021) presented a learning adaptive force control concept based on real-time object stiffness detection for medical robots. (Calanca and Fiorini, 2018) analyzed the behaviour of an adaptive force controller for series elastic actuators in very different environments.

However, control of process forces in production machines with electromechanical feed axes is still a developing field and offers space for potential improvement. The focus of this work is on the development of an adaptive control concept that automatically reacts to different and changing environmental conditions during the process. This ensures the stability of the control loop. In addition, the adaptation concept with all calculation algorithms is implemented directly on the machine control and is real-time capable.

In the next section, the adaptation concept, its components and functionality are explained. Section 3 deals with the experimental set-up. The simulation results are described in detail in section 4. Subsequently, the execution of the experiments and the validation of the control concept are presented in section 5. The publication concludes with a summary and outlook.

2 ADAPTIVE CONTROL

The application of an adaptive control concept is suitable for preventing poor performance or instability caused by deviations of the controlled system or non-linearities. Non-linear adaptive controllers have the ability to adapt the controller parameters of the basic control loop automatically during the process to a changing or unknown process behaviour by means of a parameter setting unit (Landau et al., 2011). With the independent adjustment, an improved performance and functionality of the controller can be achieved. A comprehensive description on the classification and categorisation of the different adaptive control concepts with regard to their mode of operation and execution principle can be found, for example, in (Åström and Wittenmark, 2013). The structure, components and functionality of the selected adaptation concept are explained in the following.

2.1 Adaptation Principle

In general, it is desirable to keep the complexity of a controller as low as possible. In particular, real-time capability must also be ensured for complex control concepts. For force control, the effective stiffness in the contact situation is the determining system parameter. Direct measurement is not possible. Therefore, a parameter-adaptive, indirect adaptation is suitable for the implementation of the control concept. Model identification adaptive control (MIAC) is used for this purpose. Here, changes in the controlled system are detected by an identification stage and the control parameters are adapted on the basis of a quality criterion. The digital, parameter-adaptive controller typically consists of the three methods of recursive online parameter estimation, the controller design procedure and the control algorithm (Isermann, 1991). The basic structure is shown as a signal flow diagram in Figure 1.

The concept is based on estimating controlled system parameters and using this information to calculate the basic control loop parameters. The calculation rule for the controller parameters is called adaptive law and results according to (Schulze and Rehberg, 1988) to:

$$\beta(t) = f(I_0;\ \alpha_P^T(t);\ \xi_P^T(t);\ k_P^T). \qquad (1)$$

The inputs of the adaptive controller are summarised in the form of the design criterion I_0, the constant vector k_P^T and the signal vector $\xi_P^T(t)$. The process parameter vector $\alpha_P^T(t)$ is calculated by means of the estimation unit. With this, the adaptation parameter of the basic control loop $\beta(t)$ is determined in the controller design unit. Here, the foot index 1 represents the parameters for the parameter estimation unit and the foot index 2 represents the parameters for the controller design unit. After selecting all free design parameters, a parameter-adaptive controller can be put into operation. In the start-up phase, however, an unpredictable transient behaviour of the controller is possible until a correct parameter estimation is available. In this case, the adaptive controller could be instable from the start. Therefore, a stable basic loop controller is kept in the control algorithm as a start model. The three essential components and structures of the adaptive controller, including the functionality, are explained in more detail in the following sections.

2.2 Control Algorithm

For the control of electromechanical feed axes, the cascade structure has established as a proven concept. It consists of several control loops that are superimposed on each other. In this application, the velocity and current controller are subordinated to the adaptive force controller. Accordingly, the control plant of the force controller consists of the subordinated velocity and current control loop, as well as the mechanics of the axis and the process. This is illustrated in the simplified signal flow diagram in Figure 2.

The influence of the process is taken into account by the effective stiffness K_E. In addition, the current control loop is shown here as a proportional-time (PT1)-element for simplification. On the test setup, both current and velocity controllers are implemented as proportional-integral (PI)-controllers. Thus, the controlled system including the process already contains an integrating part. Therefore, the force controller can be designed as a proportional (P)-

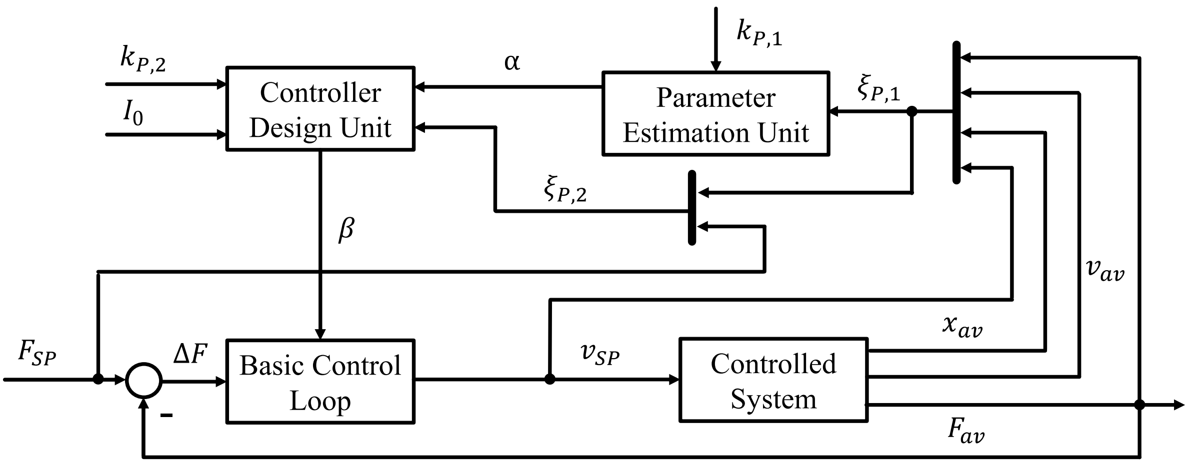


Figure 1: Block diagram and signal flow diagram of the parameter-adaptive controller.

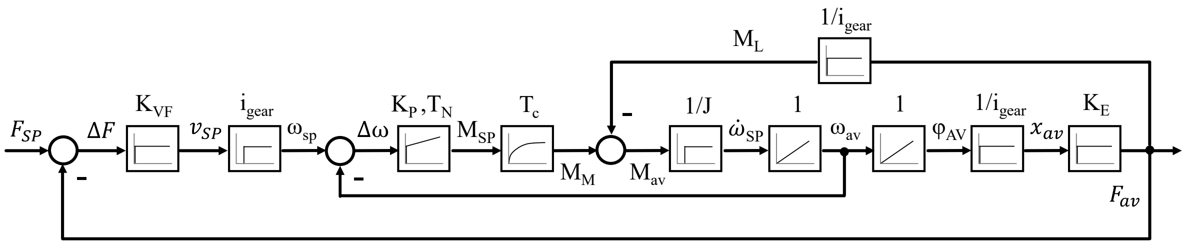


Figure 2: Simplified signal flow diagram of the basic control loop and the controlled system.

controller. This offers the additional advantage that it can be designed quickly and easily with just one parameter. Moreover, only one parameter then has to be calculated and adapted during operation. This results in less complexity, error-proneness and calculation time, which favours real-time capability.

2.3 Controller Design Unit

The controller design is based on the setting rule for the symmetric optimum (SO). This method is a common design procedure for the controllers of integrative-time (IT1)-systems. It has also proven to be suitable in previous investigations to achieve good performance. A more detailed description of this can also be found in (Sewohl et al., 2020). Thus, the gain factor K_{VF} for the force controller is calculated according to the following equation:

$$K_{VF} = \frac{1}{a * K_E * T_{Vel}}. \tag{2}$$

Here a corresponds to the damping factor, which is usually set to the value 2. The parameter T_{Vel} represents the substitute time constant of the subordinated system. The integral gain of the force control loop is determined by the effective stiffness K_E. While the other parameters are constant, this value varies in the process, which can lead to instability in conventional control concepts. The adaptive controller is aimed at making the stability and performance of the closed-loop force control largely independent of the stiffness K_E. In order to achieve this, the gain K_{VF} of the force controller is adjusted in the programmable logic control (PLC)-cycle of the control system every 2 ms. This requires the determination of the stiffness during operation. Direct measurement is not possible, so a parameter estimation unit is implemented for this purpose, with which online estimation is carried out continuously. The estimated stiffness $\widehat{K}_E$ is transferred to the controller design unit and replaces K_E. In this way the gain factor is calculated accordingly the SO.

In addition, further monitoring functions are implemented in the controller design unit. For the detection of a setpoint violation, a comparison of the actual force value and the force setpoint with the permissible difference is made. If the force control loop starts to oscillate with a low force or displacement amplitude, no stiffness estimation is performed and a permanent instability may occur. Therefore, oscillation detection is performed using a sign comparison of the velocity setpoint from the current and previous PLC-cycle. If one of these criteria is violated, the parameter set for a stable basic control loop is used. This is based on the maximum stiffness of the controlled system. Thus, a backup controller is kept available for critical operating situations. After the force control loop has been stabilised by the backup-controller, a continuous stiffness estimation and parameter adaptation takes place again.

2.4 Parameter Estimation Unit

Good adaptation performance requires estimation of the effective stiffness as quickly and with as little noise as possible. The estimation time is particularly relevant for rapid increases in stiffness. In this case, the force controller amplification is too high, which results from the previous, lower stiffness. Thus, in the event of a sudden increase in stiffness, there is a risk of overshooting of the actual force value and even instability of the force control loop. The low-noise estimation is necessary because the estimated stiffness directly influences the velocity setpoint. For a strongly noisy parameter estimation, permanent and distinct acceleration and braking phases would follow. These could both reduce the lifetime of the servo drive and negatively affect the quality of the stiffness estimation due to dynamic inertia effects. Thus, the task of the parameter estimation unit is to estimate the effective stiffness online as quickly as possible and at the same time with as little noise as possible. This is essential for the functionality of the adaptive controller. The basic structure is shown in Figure 3. The parameter estimation unit consists of

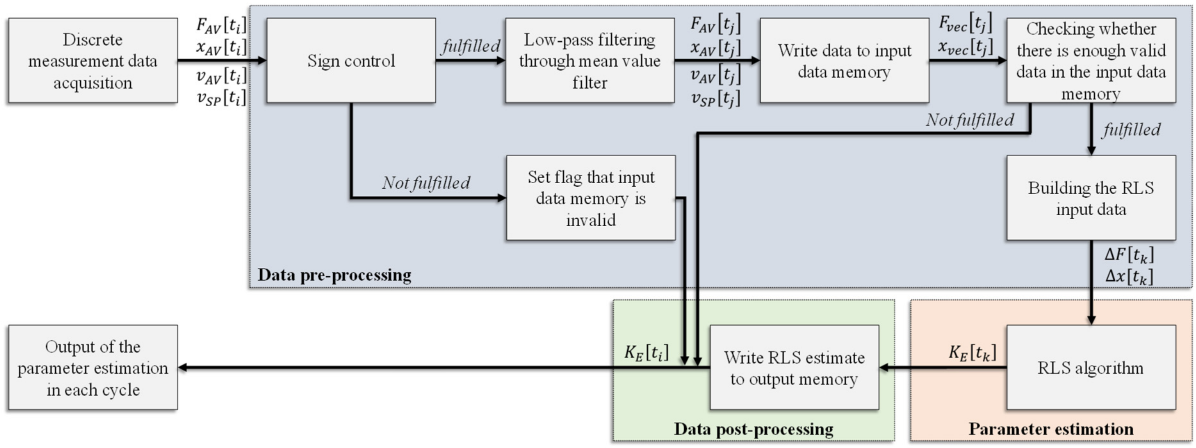


Figure 3: Basic structure and functionality of the parameter estimation unit.

the three steps of data pre-processing, parameter estimation using the RLS-algorithm and data post-processing. The detailed explanation of the design, functionality and validation of the parameter estimation unit is given in (Norberger et al., 2022).

2.5 Mode of Operation

The sequence of the PLC-program with the adaptive force control consists of two basic sections. In the first initialisation phase, the tool is moved at a defined feed rate until a threshold force is reached. The initialisation phase is necessary to obtain a reliable estimate $\widehat{K}_E$ of the effective stiffness K_E. An exemplary value for the threshold force is, for example, 50 N. When the threshold force is exceeded, the initialisation phase ends and the adaptive force control is activated. The adaptation cycle of the controller runs with the following steps:

1. Initialisation: The process image as well as the design and control parameters are imported. The associated cycle time corresponds to the PLC working cycle.

2. Calling the parameter estimation unit: The stiffness is estimated from the current measured values. The stiffness value $\widehat{K}_E$ is then output. If no new stiffness estimation has taken place, the last estimated value is used. Thus, a stiffness value is available in each PLC-cycle. When the adaptation unit is switched on, the initialisation estimate is output first, which is gradually adjusted by current estimations.

3. Calling the controller design unit: Here, the calculation of the force controller gain K_{VF} takes place on the basis of the SO. The information about the force and velocity signals is also transferred to the monitoring functions.

4. Adaptation: The controller parameter K_{VF} is overwritten in the control loop. This parameter is used to control the electromechanical feed axis in the current cycle.

The controller gain is continuously adapted after the initialisation phase according to the previously described steps.

3 TEST SETUP

A test-setup of an electromechanical feed axis with a control from Beckhoff was selected for the implementation and validation of the control concept. The basic structure of the test-setup with the individual components is illustrated in Figure 4. The sequence programs and operating modes, the force control, the controller design unit with the adaptation algorithm, the parameter estimation unit and the setpoint generation are implemented in the IPC. This means that all algorithms are implemented directly in the control system. In addition, the IPC is coupled via the backplane bus with the safety modules, I/O modules and the measuring amplifier for the force sensor. In this way, the communication times are reduced from the millisecond range to the microsecond range and the performance can be increased. The servo inverter is connected via the EtherCAT connection. The subordinate velocity and current control are located here. The servo motor is controlled here, too. In the mechanical part, the rotational movement of the servo motor is synchronously transmitted to the two ball screw spindles via several belts and gears. Here exists a mechanical forced coupling. The rotational movement is converted into translation via the nuts and the crosshead attached to them. In the workspace,

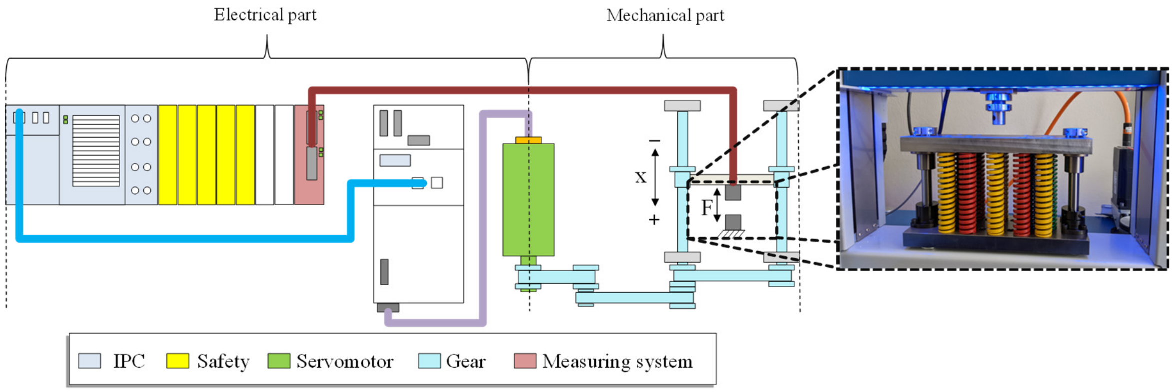


Figure 4: Experimental setup and schematic structure of the electromechanical feed axis.

the load is applied to the workpieces via the crosshead, in which the sensor for detecting the process forces is also integrated. The experimental setup is designed for loads up to 10 kN. A modular and exchangeable spring package was designed in order to cause reproducible deviations and non-linearities in stiffness. This load module is used to simulate a process or a resulting process force. In this way, variable load characteristics can be initiated with high reproducibility by a movement of the axis against the load module. This allows systematic replication and investigation of changes and deviations in the system stiffness for adaptive force control. More detailed information on the individual components, the commissioning and parameterisation of the test setup can also be found in (Sewohl et al. 2020).

4 SIMULATION

The development of the adaptive control concept was accompanied by model-in-the-loop simulations. MATLAB/Simulink serves as the simulation environment. The generation of a simulation model for the test setup has the goal of cyclically providing the adaptive control system with a realistic process image for iterative function tests. For this purpose, the essential components of the adaptive control, such as the control algorithm, the parameter estimation and the controller design unit are created in separate function blocks. The mechanical model of the test setup was also inserted in a single subsystem. Due to the modular structure, the adaptive control can be iteratively tested and improved independently of the test setup. Using the TwinCat C++ target for Matlab/Simulink and the Simulink coder, it is possible to export the control algorithm directly to the Beckhoff machine controller.

To simulate the real system behaviour, the mechanics of the test setup were implemented in the simulation model as a 2-mass oscillator. The relevant parameters, such as stiffnesses, damping, mass moments of inertia and transmission ratios, were determined from the technical data sheets and the CAD-model. In addition, the signals are also approximated as closely as possible to reality. For this purpose, the corresponding sampling frequencies, quantisation and noise behaviour were determined on the experimental setup and transferred to the control structure of the model. Computing and communication times in the control system were also taken into account. The implementation of a friction model was dispensed with. The parameterisation of the control was carried out according to the procedure and parameters from (Sewohl et al., 2020).

Based on the comparison of real measurement data and the response of the simulation model, a verification of the model behaviour for relevant operating situations was carried out. The behaviour of the force control was examined for different stiffnesses, force amplifications and setpoint profiles. It was checked whether the Simulink-model can represent the behaviour of the test setup with sufficient accuracy for the controller design. The contouring error as well as the starting and braking behaviour are particularly relevant for this. The results for a trapezoidal force setpoint profile are shown in Figure 5. Up to the threshold value of 100 N, the feed axis is moved under velocity control. Afterwards, the system switches to force-controlled operation. A comparison of the contouring error as well as the starting and braking behaviour shows that the simulation model reproduces reality very closely. Therefore, it is suitable for the development and testing of the adaptive force controller. In addition to the control structure, the controller design unit and the parameter estimation unit were integrated into the

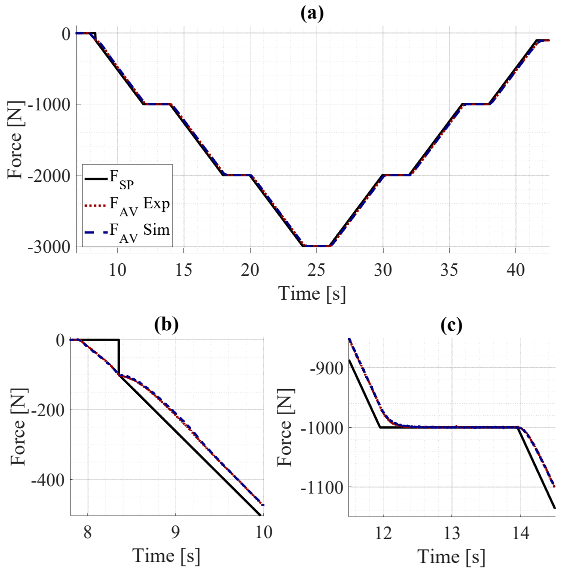


Figure 5: Comparison of actual force values from simulation and experiment. (a) Overview of the force profile. (b) Switching process. (c) Transition area.

model. The parameter estimation unit acts independently of the mechanical behaviour of the test setup and has already been validated in (Norberger et al., 2022).

The testing of the adaptation concept in interaction with the parameter estimation unit and the controller design unit is first carried out in the simulation environment using various stiffness jumps. The reaction of the adaptive controller to a stiffness jump from 100 N/mm to 500 N/mm is shown in Figure 6. The diagram shows that the adaptive controller is able to ensure a stable control loop in the case of abrupt changes in the system behaviour. This applies both to abrupt increases and decreases in the effective stiffness K_E. In this case, the contouring error is also temporarily reduced or increased. After about 50 ms, the parameter estimation unit fully adjusts to the jump in stiffness and the adaptive controller compensates the contouring error again. In contrast, the conventional controller becomes instable shortly after the change in stiffness. For better illustration of this case, the data are only displayed up to the time point of 5.5 s.

For the controller design, there is a freely definable influence parameter with the design parameter $I_0 = a$. This parameter is first varied in the simulation and the results are shown in Figure 7. Through the investigation, the effects and further modification possibilities can be assessed. The force curve shows that the parameter a has an effect on the performance. Smaller values cause smaller and higher values correspondingly larger contouring errors. However, small values also increase the risk of overshooting in the event of abrupt changes and the control loop becoming instable. But this can be avoided by the implemented safety functions. In the event of a setpoint violation, the parameter estimation is stopped and the backup-controller is used. This is illustrated in diagram (b). Diagram (c) shows the characteristic of the controller gain K_{VF}, which is adjusted on the basis of the stiffness estimate $\widehat{K}_E$. In the case of a setpoint violation, the calculation is re-initiated. As soon as the parameter estimation unit delivers reliable values again, the controller parameter is automatically adapted.

The considered example with a sudden increase of the stiffness from Figure 6 is to be considered as a critical application. With a large change in the controlled system parameters, there is a risk of an instable control loop. It was shown that the developed control concept nevertheless remains stable for this critical case and the desired adaptation takes place. In reality, such jumps are not to be expected at the test setup. Therefore, the behaviour for a further stiffness

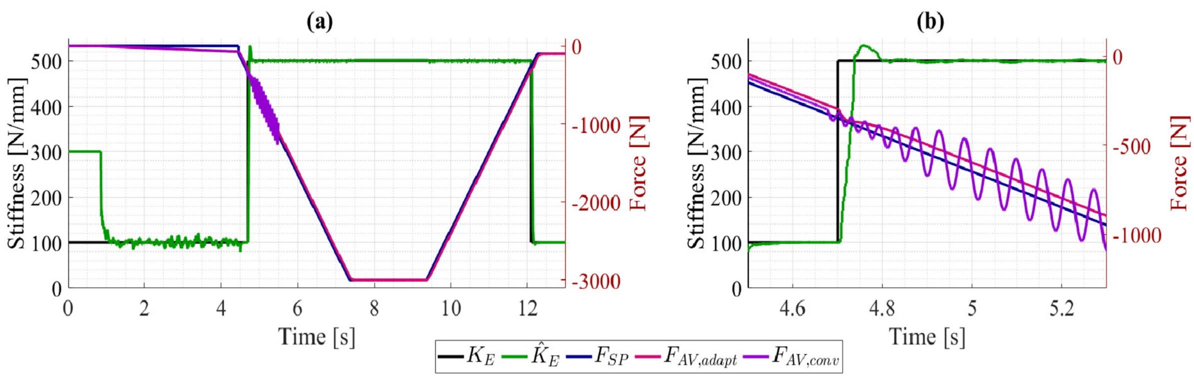


Figure 6: (a) Overview of the simulated behaviour of the adaptive and conventional controller during a stiffness jump. (b) Detail of the stiffness change.

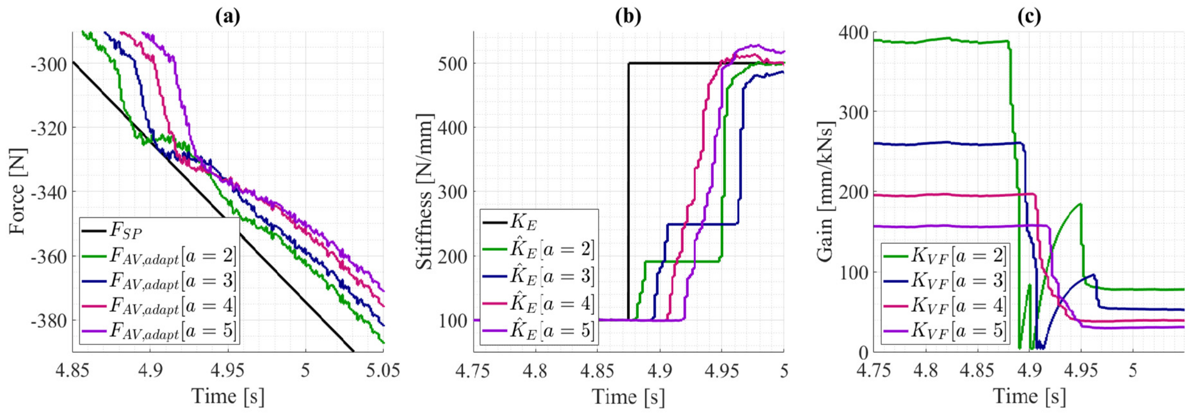


Figure 7: Influence of the design parameter a on the behaviour of the control system. (a) Comparison of the actual force values. (b) Comparison of the stiffness estimation. (c) Comparison of the controller gain.

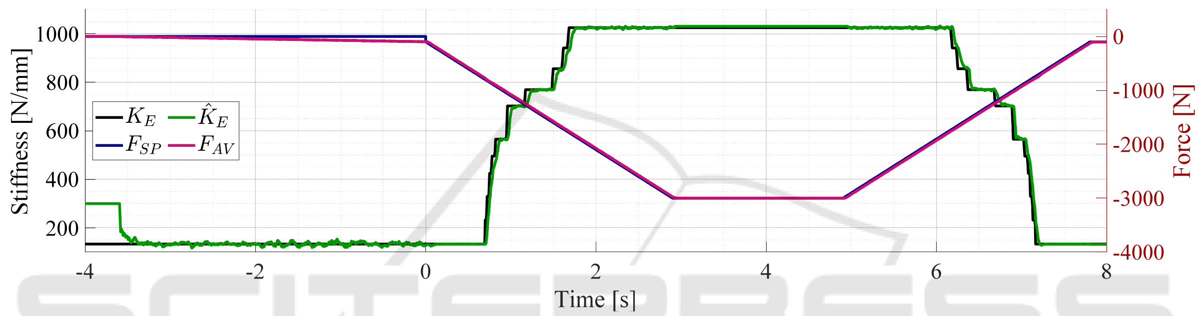


Figure 8: Complete profile of forces and stiffnesses for the simulative investigation of the adjusted stiffness profile.

profile is examined in the simulation. This is approximated to the characteristic curve of the test setup. Here, a staircase-shaped increase in stiffness from 130 N/mm to 1000 N/mm is distributed in several steps over the stroke process. The variation range of the stiffness corresponds to the variation that can actually be generated with the spring assembly. The result is shown in Figure 8. Here it can be also seen that the adaptive controller remains stable and can follow the setpoint profile very well over the entire range of variation of the stiffness change. This is true for both compression and decompression. Thus, the basic functionality of the concept could first be proven in the simulation.

5 EXPERIMENTS AND VALIDATION

In order to transfer the adaptive force control developed in Matlab/Simulink to the test setup, it is necessary to integrate the function modules into the control system. Beckhoff allows direct integration of the Simulink-model in the machine controller. For this purpose, the model is translated into C++ code using the Simulink code generator. The TE1400 TwinCAT Target can be used to generate a TwinCAT Component Object model (TcCOM) from the code (Beckhoff, 2020). The TcCOM has the inputs and outputs defined in the Simulink model and can be linked to a corresponding task in the Beckhoff development environment. The inputs and outputs are linked with the associated variables from the process image. In this way, the two function blocks for adaptive control with the parameter estimation unit are transferred directly from the existing Simulink-model to the real machine control. The algorithms are integrated in the runtime of the machine control and are processed cyclically in real-time.

The practical testing of the concept is carried out with the help of the modular spring package shown in Figure 9. By combining the springs and using spacer elements, variable path-dependent non-linear stiffness characteristics can be specified. The adaptive control concept is validated using the two illustrated spring configurations with different stiffness profiles. At the beginning of the compression of the spring assembly, only 4 springs are engaged. Only when the spring assembly has been

(a) **(b)**

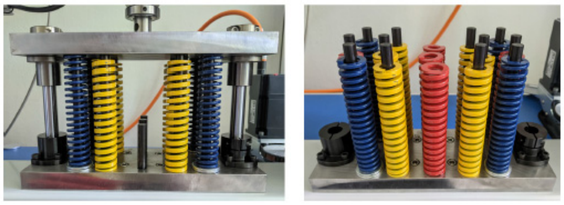


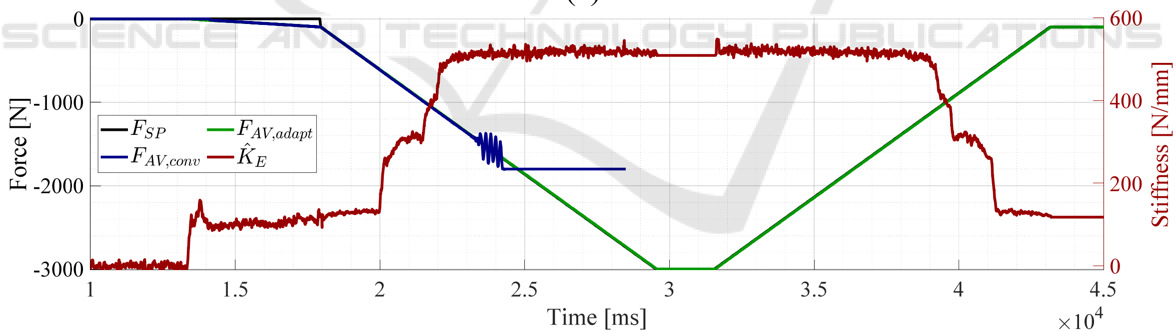
Figure 9: Combination of spring elements for stiffness jumps. (a) Change S1 from 130 N/mm to 500 N/mm. (b) Change S2 from 130 N/mm to 1000 N/mm.

compressed by a certain deflection do the other springs engage. This results in a rapid increase in stiffness. Due to the manufacturing tolerances of the springs, there is no abrupt jump in stiffness. Rather, the increase in stiffness from the initial to the final stiffness takes place within a transition range of around 2 mm. The complete curves of the measurements for the two spring configurations are illustrated in Figure 10. The behaviour of the conventionally tuned force controller is also compared here. Corresponding to the composition of the spring assembly, the initial stiffness results in K_E = 132 N/mm. The conventional controller was set to this system behaviour without adaptation according to the SO and the design parameter a = 2.

During validation, the behaviour was examined at several rates of force change (1000 N/s, 500 N/s and 250 N/s). Figure 10 (a) shows the behaviour for 250 N/s and a stiffness jump to 500 N/mm. In Figure 10 (b) the stiffness changes to 1000 N/mm. The stiffness changes are well reproduced by the parameter estimation unit. It can also be clearly seen that the conventional force controller becomes instable and oscillates without adaptation in both cases. Therefore, the tests were stopped at this point by the implemented safety function and the data recording was interrupted. The conventional force control also became instable during all other tests. In contrast, it is also clear that the adaptive controller reacts very well to the change in system in practice and follows the setpoint profile without any instability occurring. This applies to all the tests carried out with the three different increases in the force setpoint ramp.

In addition, the effects resulting from a variation of the free design parameter a were also considered. The results for a force increase of 1000 N/s are shown for the stiffness jumps in Figure 11. It can be seen that the performance of the adaptive controller can be influenced with the free design parameter. With smaller factors, the following error decreases, as in the simulation. However, this also increases the proneness to errors and the tendency to oscillate.

(a)



(b)

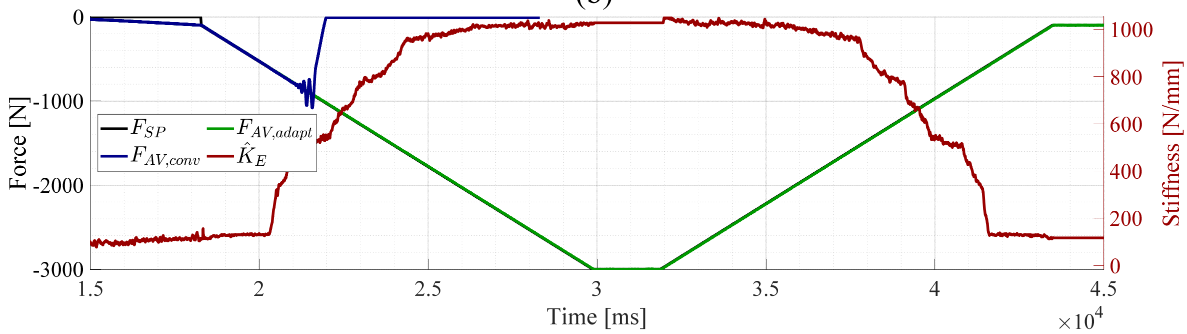


Figure 10: Experimental validation of the adaptive control concept. (a) Results for the stiffness jump S1. (b) Results for the stiffness jump S2.

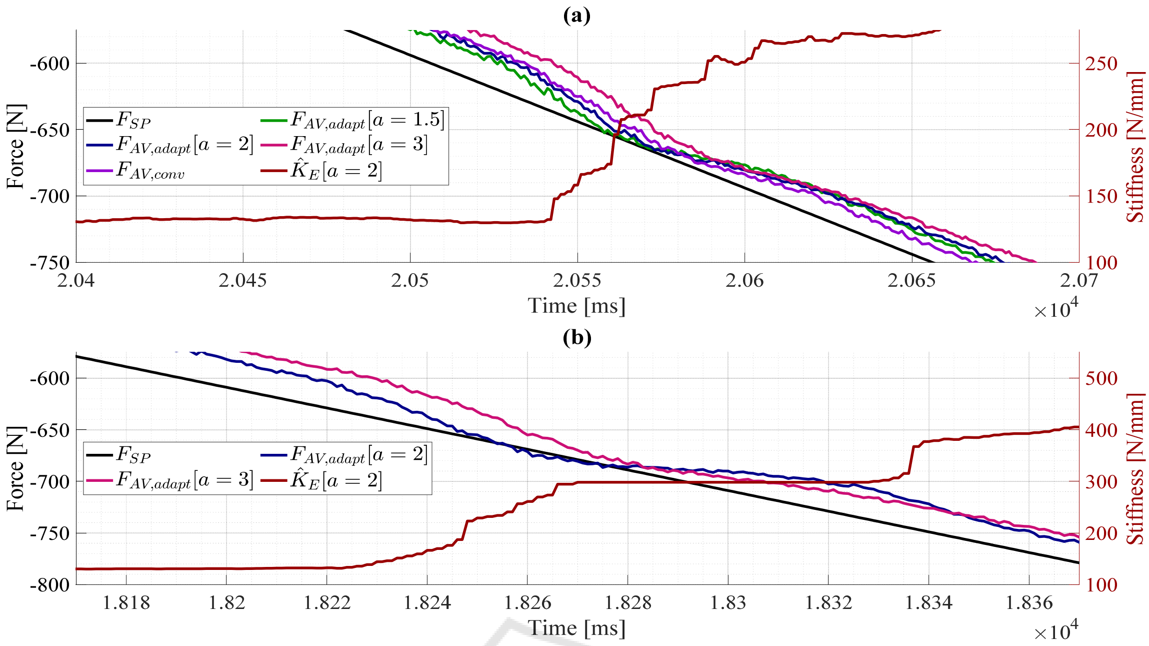


Figure 11: Measurement data of the adaptive and conventional force control for the force increase of 1000 N/s and different design parameter a. (a) Stiffness change S1. (b) Stiffness change S2.

Conversely, larger factors result in an increased contouring error. However, this also increases the robustness of the control. Furthermore, the back-up controller was implemented for the adaptive controller as an additional safety criterion on the test setup. This is designed for the frame rigidity of the machine and intervenes as soon as a setpoint violation occurs. The adaptation process is then restarted. This functionality of the safety mechanism is illustrated in Figure 11 (b). Here the stiffness jump S2 is shown for a force increase of 1000 N/s. For the design factor a = 2, a setpoint violation occurs with the change in stiffness. In this case, the input data memory of the parameter estimation unit is reset, the estimation is stopped and reinitialised. This is expressed in by the horizontal line of the parameter estimation value $\widehat{K}_E$. As soon as sufficient input data are available, new estimated values are transferred and the adaptation process is continued. This is the case here after about 60 ms. It can also be seen that the control then stabilises and adjusts to the changed system. With the use of the backup controller, the functionality of the adaptive controller can also be ensured for critical operating situations in practice.

6 SUMMARY

In this paper, the concept of an adaptive force controller for an electromechanical feed axis was presented. The individual components, the structure and the mode of operation were explained. The algorithm was first tested and optimised on a model in the simulation environment. The concept was then transferred to the test setup and experimentally validated. In the context of this, the adaptive controller was exported by means of the Simulink-coder. The TcCOM was instantiated in the machine controller and linked to the corresponding tasks, which are processed in real-time on the PLC. The adaptive controller behaves identically on the machine controller to the Simulink-model in Matlab. This principle allows optimisations and further developments to be carried out modularly in Matlab/Simulink and implemented with little effort.

Furthermore, it was proven in the scope of the work that the developed controller with the parameter estimation unit is capable of detecting changes in stiffness and reacting to them accordingly. This applies to both compression and decompression processes. The adaptive controller is able to adapt the gain factor to the controlled system during operation based on the estimated stiffness. Even with highly variable system behaviour, the controller remains stable due to the adaptation of the gain factor and improved performance is achieved. In addition, the use of the backup-controller ensures functionality even for critical operating situations. The behaviour of the adaptive control can basically be influenced by the choice of design parameters for the parameter estimation unit and the controller design unit. Compared to conventional control with unchanging parameters, an improved compromise between stability and performance is achieved. This is especially true if essential parameters of the controlled system are not known a priori or are time-variant. For small stiffness values, the adaptation enables a higher proportional gain. At the same time, improved stability was achieved in the range of larger values. The investigations also demonstrated the real-time capability of the developed control system. Depending on the process, changes in the controlled system are already compensated after 40-50 ms.

7 CONCLUSION AND OUTLOOK

The adaptation concept presented can be transferred to many areas in production technology and offers a wide range of applications. A major limitation of the method is currently that the process force must be dependent on the stiffness. Potential use cases are, in particular, forming processes, material testing, grinding, joining and assembly operations. The concept can be used on machine tools, forming machines and robots. Here, an analysis of the system behaviour should first be carried out. This allows the design parameters for the parameter estimation unit and the controller design unit to be adjusted and optimised to the corresponding application. In addition, the fast responsiveness and real-time capability are an essential characteristic of the concept. For processes where the stiffness changes very slowly, the design parameters and limits of the parameter estimation algorithm have to be adapted. In principle, it is also possible to transfer the concept to more complex processes with different conditions. In the case of machining operations (such as milling), it could be used for individual force components. Furthermore, the algorithm could also be extended or supplemented with process models that take into account additional influencing variables.

Future work will focus in particular on investigating possibilities for improving the learning phase and the switchover process for adaptive control. In addition, an optimisation of the empirically set design parameters is intended in further investigations. The extension of the algorithm with a compensation of weight and acceleration forces is also aimed at. Furthermore, the suitability and effects of other control structures in the control loop shall be investigated. The safety functionalities also still offer potential for improvement.

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