CHALLANGES OF CONVENTIONAL EQUIPMENT ON MODEL BASED CONTROL CONCEPTS

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Abstract

In this paper experimental results of the so called IDOB control approach are presented for the example of a single axis linear electric drive control. In this concept an inverse nominal plant model is required, which is composed and inverted based on the simulation tool Dymola in Modelica language. The inverse model is used as Block within a Simulink environment to take advantages from the real-time abilities of RTW/xPC-Target. For the arrangement of a hardware-in-the-loop scenario, the usual drive communication interface Sercos was developed for this environment. By the simulation and experimental results an impressive performance can be demonstrated of the presented control approach as well as of the concept of methodical tool-based model processing by means of Dymola.
However on the one hand, herewith a closed workflow is established for the formation of overall control concepts of multi-axes kinematics systems. This emerges as an approach for a qualified control design for such robotic systems with controller based motion performance. On the other hand considerable remaining limitations appear in case of decentralized architectures. Single axis controllers, which are integrated in advanced control loops by digital communication systems, are characterized by destructive delays. To that effect new requirements are derived for future generations of such interfaces.

Keywords: Object oriented modelling, realtime simulation, inverse disturbance observer, multi-axeis drive control, decentralized architectures

Presenting Author's Biography

Markus Krabbes studied 1991-1996 electrical engineering at Leipzig university of technology. He began work as scientific assistant at the Ilmenau university of technology in the field of cognitive robotics. 1998-2001 this research was continued at the Magdeburg University with research on dynamics modeling and control of industrial robots by means of neural networks and was finished with PhD. From 2001-2003 Mr. Krabbes worked as group leader at the Fraunhofer institute on machine tools and forming technology in Chemnitz focused on control of parallel kinematics. Since 2003 he is Professor for information systems at the Leipzig university of technology, department of electrical engineering and information technology. Main research interests are simulation based tool chains for control design and motion control of mobile and robot systems.

ISBN 978-3-901608-32-2

1 Introduction

In the last years electric drive systems made remarkable improvements. The basis for this has been the rising energy density and dynamics of drives in connection with integrated drive control with highest resolution in time and motion. The excellent reference and disturbance reaction behavior of these drive systems in the controlled loop is sufficiently to operate most kinematics structures with limited multi-variable characteristics in decentralized single axis control. However, non-orthogonal structures like e.g. industrial robots or parallel kinematic machines (PKM) still have potentials for lasting improvements by centralized MIMO controllers. But there are further structural requirements on such extended approaches. In order to keep subordinate control loops based on available equipment, interventions have to be realized as pilot signals added to the original reference signal. For this aim, model based concepts are available, which can be methodically developed by means of tool-based realtime simulation. In this scenario the role of simulation tools is further expanding from analysis and evaluation to direct synthesis.
For the control of multi-dimensionally actuated production machines the practicable control architecture replaces within the control loop the unmeasured part of the open kinematic chain between the tool center point (TCP) and the nearest(latest) position sensor by an appropriate static and/or dynamic upstream model. The reason for this is not only the any longer undeveloped sensor technology for the spatial measurement of the real TCP position with necessary characteristics concerning accuracy, resolution, scanning rate, delay and not least costs. Even in case of complete satisfaction of these requirements, the benefit linked with it is limited to the geometric accuracy and improved damping if applicable.
Drive near sensors and based on it short control loops remain essential for high-dynamic performance. Only thus the electrical servo controllers can be dimensioned sufficiently tight for decentralized operation in subordinated SISO structures. The model of kinematics connected to the control loops is assumed as *rigid* and considers only the corresponding static behavior. This simplifies substantially the necessary steps to its structural design, inversion and integration into the control system. Only the experimental identification of a machine-individual kinematics model with the necessary accuracy is currently main subject of scientific work and is referred as calibration.
In contrast to this, further research is needed for each of the mentioned steps concerning the all dynamic effects of the open chain: starting at the model design over its inverting and control integration up to the experimental identification. Based on the abilities of modern object-oriented simulation tools like Dymola, the automated generation of inverse models offers a tool-based implementation of the presented approach.

2 Control approach

The integration of a dynamic model into the control system of a multi-axis kinematics structure can be decomposed into two fundamental problem fields: on the one hand non-ideal and load-sensitive tracking behavior $\mathbf{G}_{drive} = \theta_{meas}/\theta_{ref} = f(\{\mathbf{F};\tau\}_{ext})$ of the axes' drive positions θ_{meas} does arise. Movements of rotatory or non-orthogonally arranged prismatic actuated joints expresses itself in unavoidable, but directly *measurable* contouring errors.
On the other hand also the elastic dynamics of the structure $\mathbf{G}_{elast} = \{\mathbf{X}_{meas};\mathbf{I}_{meas}\}/\{\theta_{meas};\{\mathbf{F};\tau\}_{ext}\}$ lead to Cartesian position errors of the TCP $\mathbf{X}_{meas}$. These error portions are actually not measurably, *only model-based assessable*, and require imperatively the consideration of external perturbing loads $\{\mathbf{F};\tau\}_{ext}$.

A nominal inverse model of the controlled system is used by the so called Inverse Disturbance Observer (IDOB) in order to produce a new reference signal, which contains an error minimizing pilot control component [1, 2, 3]. Because this controlled system can be a subordinate closed loop system as well, the nominal model can be appropriately extracted from its ideal transfer function.

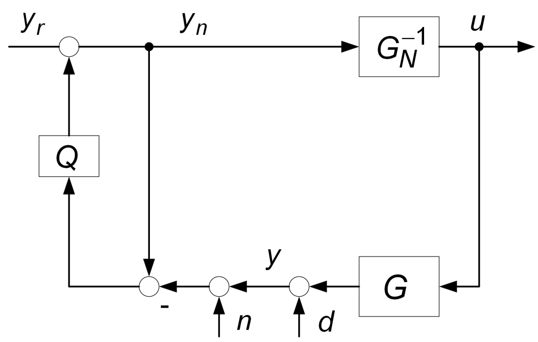

Fig. 1 IDOB control scheme

The fundamental structure as pictured in figure 1 is based on a (nominal) inverse plant model and a feedback structure, which approaches within the bandwidth of the (unity gain low pass) filter Q the total behavior of the series connection of inverse model $\mathbf{G}_N^{-1}$ and plant $\mathbf{G}$ to 1. In the case of IDOB control (cp. in contrast Disturbance Observer control DOB [2]) an upstream model-inverse $\widetilde{\mathbf{G}}_N^{-1}$ produces accurate tracking, because the inverted model behavior is matched to the real plant. This correction effect makes it possible to work also at unstable plants with a stable approximated model-inverse [1].

According to the decomposition as introduced in tracking behavior of the drives and elastic machine dynamics, IDOB control is used in this paper cascaded into two structures as in figure 2 based on inverted model components. Within an inside loop ideal tracking of

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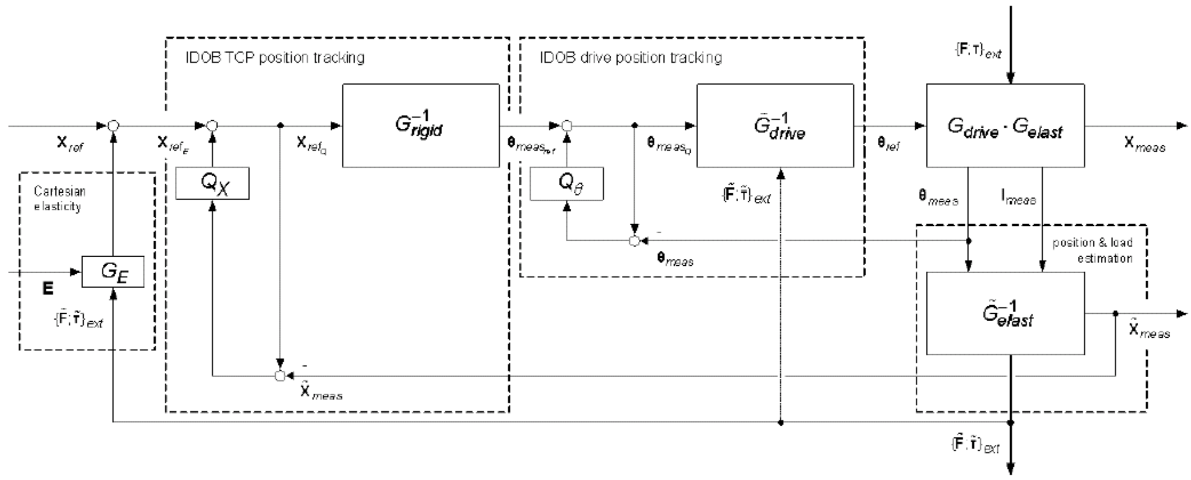

Fig. 2 Cascaded IDOB control scheme of multi axes system

the drives is aimed by an inverting of the position controlled drives. By implementation of in this case rigidly assumed machine dynamics all changing inertia effects can be considered as well as influences of the coupling of the drives and external perturbing load. Hence, this model is quite accurately and permits a IDOB feedback filter Q_θ of high bandwidth for best performance of control.
For the tracking of the Cartesian position, the overall system can be enclosed by a further IDOB. The nominal inverse model is formed here from an ideal coordinates transformation according to the rigid geometrical model. In order to close this outmost control loop, a measuring signal of the TCP position is required, which is not actually present however. Therefore a further, partially inverted model is used for its estimation, which supplies apart from the TCP position also the external perturbing force and torque based on the measurable values of drive position θ_{drive} and drive load represented by the coils current $\mathbf{I}_{meas}$.

3 Modeling and realization concept

Utilization of the simulation system Dymola represents a promising approach for a completely tool based solution of the steps of modeling and implementation by means of object oriented modeling based on Modelica. The overall model $\mathbf{G}_{drive} \cdot \mathbf{G}_{elast}$ (e.g. of robot's kinematics) is able to simulate the drives including their friction effects and integrated controllers as well as the physical layout. For this, many standard models of the Modelica library and a few own special models can be used. Input signals of this plant model are the reference trajectories of the drive controllers and the external load. Output signals are the measurable drive positions and forces and the actual Cartesian TCP position. The control structure has now to be completed with inverted and semi-inverted versions of the overall model. For this, just some `TwoInputs` / `TwoOuputs` - blocks to the input and output connectors of the overall model had to be added (Fig. 4) [4]. The Modelica translator process of Dymola derives according signal directions automatically.
The results of this processing has been shown in [3] very impressively not at a serial kinematics systems like an industrial robot, but at an example of a PKM named 'Black Beetle'. This hexapod is a 6 DOF movable mechanical system for handling or other machining with high structural stiffness and small dead load, because all drives are fixed with the machine frame (Fig. 3).

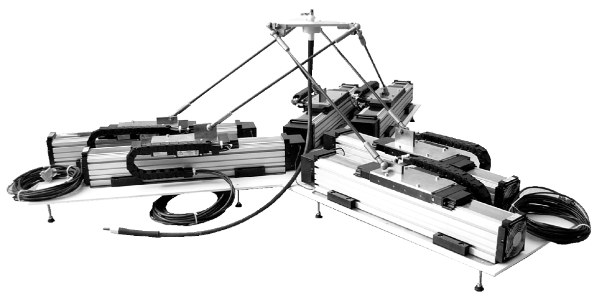

Fig. 3 Parallel kinematic machine *Black Beetle*

In figure 4 the step is illustrated from the forward modeling of the PKM to the inversion of this iconized model. In a complete simulation environment impressive results has been achieved based on the control approach as in figure 2 [3].

In order to perform the required evaluation at the real robot system, the Dymola-model has to be transfered into a real-time environment with Hardware-in-the-Loop abilities. This is offered by an integration in MATLAB/Simulink, because its real-time extension can deal also with for it exported Dymola-blocks. By means of a specially implemented driver for an active PCI-SERCOS-Interface, a HIL-scenario for electric drives can be realized by means of the xPC-Target environment. The SERCOS bus is a common standardized real-time interface for the communication of computer numeric controls with the decentralized drive

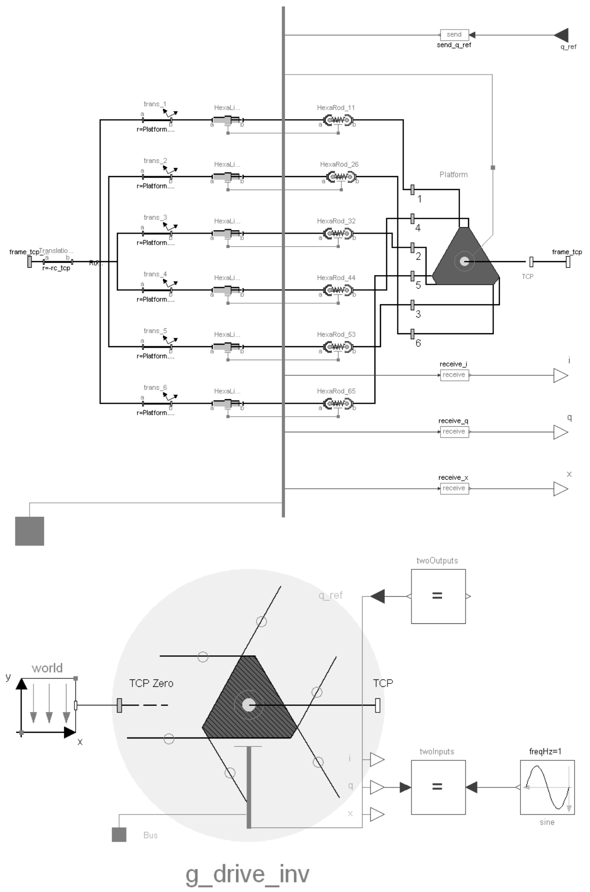

Fig. 4 Inversion example of the overall PKM model; top: plant model, bottom: formation of the inverse system.

controllers. The signal ports are integrated in Simulink models by simple blocks with according configuration dialogs (Fig. 5, 6). Very important is the ability of bidirectional data transfer between numeric and drive controller. Hence, not only reference values are downloaded, but also the actual values are uploaded. While this back channel is rarely used in standard applications, it is necessary to close the centralized control loop.

In Figure 7 the resulting steps of an implementation workflow a structurized:

1. Implementation of the controlled system in the required level of detail.
2. Inversion of the controlled system for usage as inverse nominal model.
3. Simulink implementation of the complete feedback structure using the inverse model.
4. Realtime application of the feedback structure by means of the xPC-Target component.
5. Completion of HIL-scenario by connection to the controlled systems via SERCOS realtime interface.

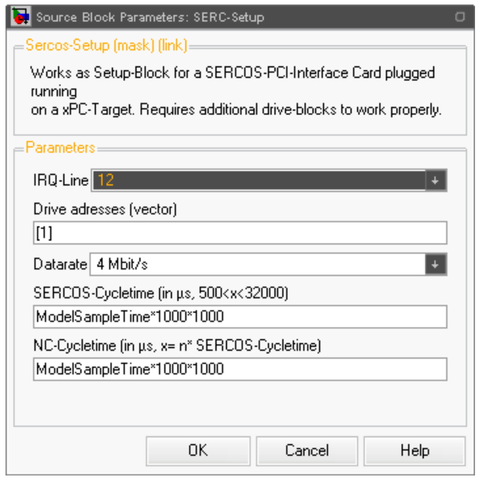

Fig. 5 Bus configuration dialog of the Sercos-Interface blockset for simulink.

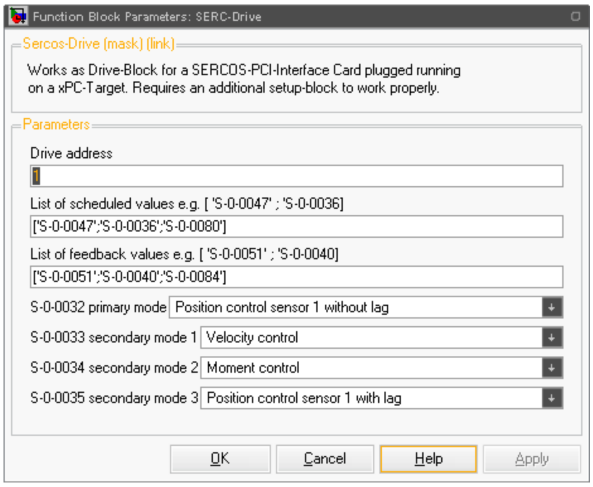

Fig. 6 Individual drive configuration dialog.

4 Experimental results

In a first step of practical evaluation the inner IDOB loop structure has been realized for one linear drive. As mentioned, the drives are connected to decentralized encapsulated control by means of cascaded PI-velocity and P-position tracking. Caused by drive couplings and a changing load, there is no generally optimal control configuration as for a single axis based on fixed load. Hence, the aim is to improve the tracking performance, but only by adapting the input signal of the drive controllers using a feedback loop that generates an error minimizing signal.
Figure 8 shows the Dymola implementation of the nominal drive model with system inverting connectors. While the reference signal q_{ref} is changed to an output, the actual drive position q is replaced by an input port.

Based on this exported Dymola block, the IDOB structure can be realized quite easily in Simulink as in Figure 9. This chart contains both elements of this loop,

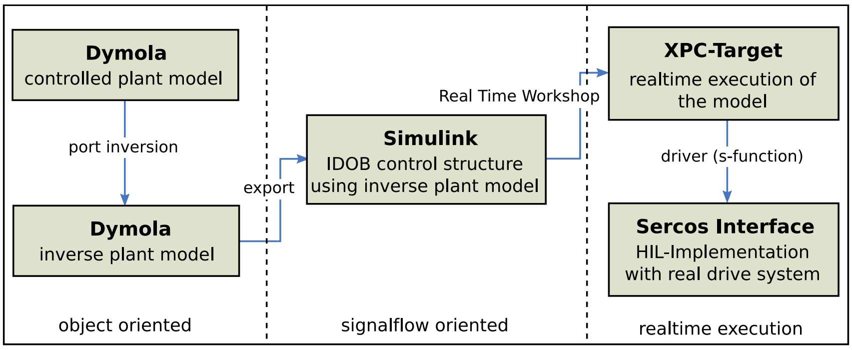

Fig. 7 Tool based IDOB implementation workflow.

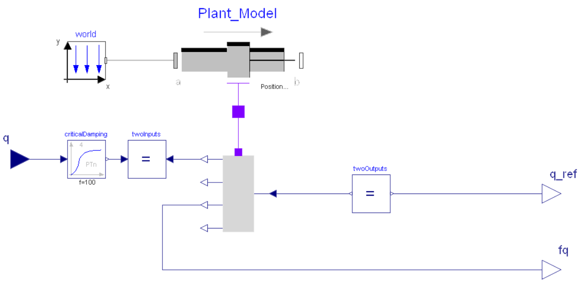

Fig. 8 Inverse Dymola plant model $\tilde{\mathbf{G}}^{-1}_{drive}$(one axis drive).

which have to be designed. On the one hand the nominal an inverse model should be given in a good trade-off between accuracy and modeling effort. On the other hand the cut-off frequency has to be chosen appropriately. The time constant of $T = 0.02$s is corresponding to a cut-off frequency at $f = \frac{1}{2\pi T} \sim 8$Hz.

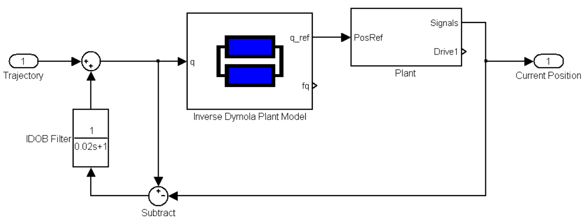

Fig. 9 IDOB structure as Simulink model.

As it can be seen in figure 10 it is possible to compare directly the tracking behavior of different structures based on the uploaded actual values. In original control, there is a remarkable delay between reference trajectory and measured motion. This time delay is not indicating immediately an insufficient control behavior, because it is dominated by the influences by Sercos communication. The value of the delay is approximately 24ms, which is corresponding to 12 bus cycle times of 2ms. The bandwidth of Sercos bus is optimized for real-time processing in the sense of data transmission without jitter between cycles and drive channels.

A general delay in all communications is not critical in contemplated applications. A real contouring error can be seen in Fig. 10 in comparison to the trajectory with pilot control, where the nominal inverse model is used without IDOB feedback loop.
Absolutely impressing is the ability of the closed IDOB loop to completely compensate this significant delay. However this advantage is bought dearly by an overshoot behavior, which is not tolerable in path tracking applications.

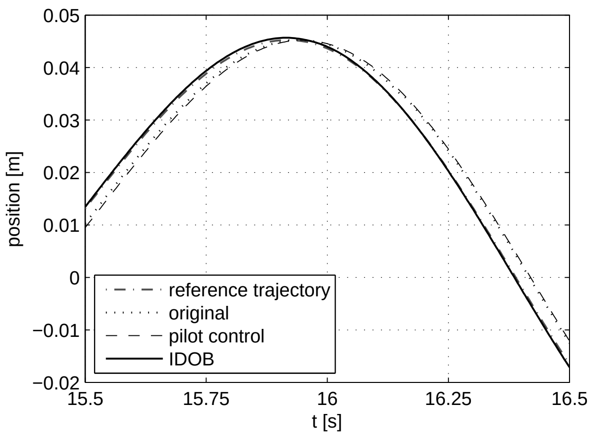

Fig. 10 Comparison of original and IDOB tracking.

Figure 11 represents the contouring errors as they are perceived by the IDOB control structure. In the real application this phase shift appears as a total delay in motion execution.
Another point is, that the inverse plant model seems to be not accurate enough to reduce the contouring error in pilot control, but IDOB is able to compensate it based on this model too. The diagram shows, that IDOB reduces the error approximately by one decade. At zero crossing of axis' velocity (as well zero crossing of contouring errors), there is a visible distortion effect in IDOB control mode because of the not perfectly invertible friction model in the nominal model.
The overall dilemma is, that the communication bus implies a maximum accuracy inverse proportional to communication cycle time. A bus delay (phase shift) will al-

ways result in a overshoot behavior of the control loop, because only signals from the late previous cycles are compared with the reference. Due to this an additional eigenfrequency is added to the signal, which appears noticeably when the axis shall rest at a fixed position. One approach is to filter this frequency out by a notch filter, but results again in a lower accuracy.

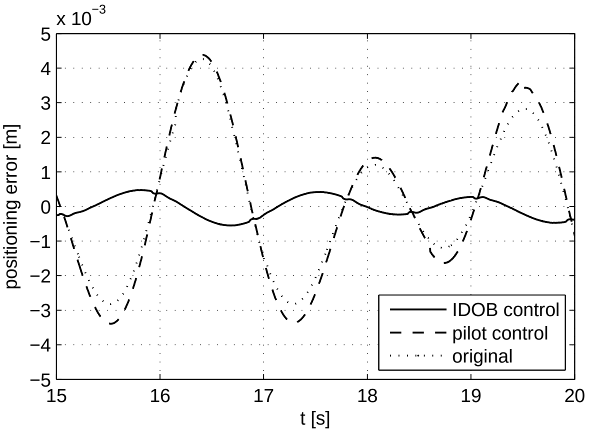

Fig. 11 Comparison of original and IDOB tracking errors.

Consequently, for practicable application of advanced centralized control approaches new requirements have to be defined and fulfilled, which consider not only jitter characteristics. The satisfactory bandwidth of current Sercos generation III should be also used for a minimized total delay of a complete data transfer through a centralized control loop.

5 Conclusion and Outlook

With the drafted procedure an approach is given, how simulation tools can be used not only for problem and design analysis, but also for control prototyping. This method is already established for mass-produced embedded systems in the automotive sector, but is not practiced for multi-axis machines. Potentially this way gives the opportunity for serious performance improvements in such kinematic systems based on advanced centralized pilot control. However, present communication systems in decentralized drive systems are not optimized to be enclosed by a control loop.

In the result of the last section two directions of further development are required. On the one hand the communication delay has to be minimized, because it is challenging the complete strategy of centralized control based on the conventional equipment structuring.

On the other hand the approach of simulation model based control design turned out effective. So this concept should be continued and extended to all single drives, therewith also the Cartesian position can be subjected to IDOB control.

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