Dynamic modeling and control of a 6 DOF parallel kinematics

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Abstract

An object-oriented modeling structure as utilized by Modelica is well suitable for the simulation of the dynamic behavior of parallel kinematic structures. Especially application of the simulation system *DYMOLA* based on this language enables an easy dynamics simulation of parallel kinematics up to creation of inverse models in the purpose of control. Based on the inverted simulation of closed loop behavior in connection with a real-time implementation new concepts of multi-axis control become feasibly. *Keywords: model inversion; inverse disturbance observer; motion control, parallel kinematic machine*

1 Introduction

Serial and parallel kinematic structures has been one of the first and best examples to explain the new quality of modeling and simulation, which is possible by means of the object oriented modeling language *MODELICA* and corresponding simulation tools like *DYMOLA*. The non explicitly solved description scheme simplifies the handling of such complex systems dramatically. However, the philosophy and architecture of Dymola permits also a change of the signal direction through complete closed loop systems. So in connection with its real-time abilities, Dymola extends his purpose from an analyzing tool by potentials in control design and code generation. This can be shown very impressively at an example of a so called Parallel Kinematics Machine (PKM). 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. 1).

For the control of almost any multi-dimensionally actuated production machine the appropriate control architecture replaces within the control loop the part of the kinematic chain behind the respectively last

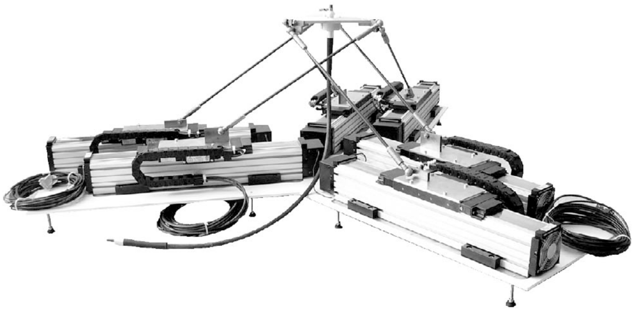

Figure 1: Parallel kinematic machine *Black Beetle*

drive position sensor by an appropriate static and/or dynamic model. Drive position sensors and based on it short control loops remain indispensable for high-dynamic performance. Only thus the electrical servo controllers can be dimensioned sufficiently rigidly, which are decentralized in subordinated SISO structures.

The model of kinematics connected to the control loops is assumed in particular with PKM normally as rigid and decoupled, so it considers only the corresponding static behavior. This simplifies substantially the necessary steps to its structural design, inverting and integration into the control system. Only the experimental identification of a machine-individual kinematics model with the necessary accuracy is further subject of scientific work and is referred as calibration. In contrast to this, development need exists for every of the mentioned steps concerning the dynamic effects of the open chain: starting at the model design over its inverting and control integration up to the experimental identification. Beyond that, the subordinated SISO drive control is to be maintained in face of extensions by centralized multi-axis controllers. Current publications are going to solve these problems by the mainstream concepts of multivariable control [3, 2]. Utilization of the simulation system Dymola represents a promising approach for a more tool based solution of these tasks by means of object oriented modeling based on Modelica. First results of investigations to that effect are presented by this contribution.

2 Inverse Models for PKM control

The integration of a dynamic model into the control system of a PKM (as well as any other multi-axis kinematic 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 drive positions θ_{meas} does arise. The non-orthonormal action of the drives 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 tool center point (TCP) $\mathbf{X}_{meas}$. These error portions are *only model-based assessable* and require imperatively the consideration of external perturbing loads $\{\mathbf{F};\tau\}_{ext}$.

This contribution suggests a compensation of these effects in the described decomposition, whereby common structures and model prototypes are used. Appropriate inverse models of the closed loop system are used by means of the so called Inverse Disturbance Observer (IDOB), in order to produce a new reference signal with an error minimizing pilot control component [1, 7].

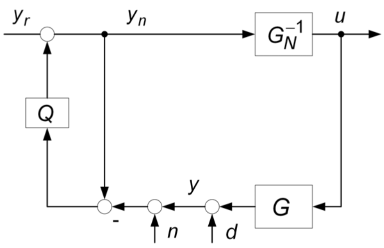

Figure 2: IDOB control scheme

The fundamental structure as pictured in figure 2 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 plant $\mathbf{G}$ and inverse model $\mathbf{G}_N^{-1}$ to 1. In the case of IDOB 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 above, IDOB is used cascaded into two structures as in figure 3 based on inverted model components [4]. Within an inside loop ideal tracking of the drives is effectuated by an inverting of the position controlled drives. By implementation of in this case rigidly assumed kinematics all changing inertia effects can be considered as well as influences of the coupling of the struts and external perturbing load. Hence, this model is quite accurately and permits a feedback filter Q_θ of high bandwidth for good performance.

For the tracking of the Cartesian position, the overall system is enclosed by a further IDOB. The ideal coordinates transformation is used here for the inverse model according to the rigid geometrical model. In order to close the 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 $\mathbf{I}_{meas}$. In this structure the outside loop is subject to various restrictions. On the one hand strong deviations between rigid model $\mathbf{G}_{rigid}^{-1}$ and position controlled plant are possible. Therefore the outside filter can be dimensioned possibly only with small bandwidth. One the other hand the overall system works with the errors of the flexible model, because the structure depends on an approximated control variable.

Also the additional estimated signals are required for a safe total behavior, since theoretical stiffness values can be impressed, which would make excessive demands of the machine structure. Therefore reference inputs with defined, homogeneous compliance are to be produced by means of this load estimation.

3 Modeling of a DOF 6 Laboratory Machine

The novel PKM named *Black Beetle*, developed at HTWK – Leipzig University of Applied Sciences in cooperation with Fraunhofer Institute IWU [6], offers the possibility to test quickly new concepts in calibration, control or machining. It is build with six in one plane pairwise arranged linear drives, which are respectively joined with the tool mounting by struts of same length (Fig. 1 and 4). With this mounting a therein fixed tool or spindle can moved in 6 directions (DOF 6).

The extreme lightweight construction and the high process speed causes not negligible tracking errors and elastic deformations, which enforces a dynamic treatment in controller design. Realtime-simulations

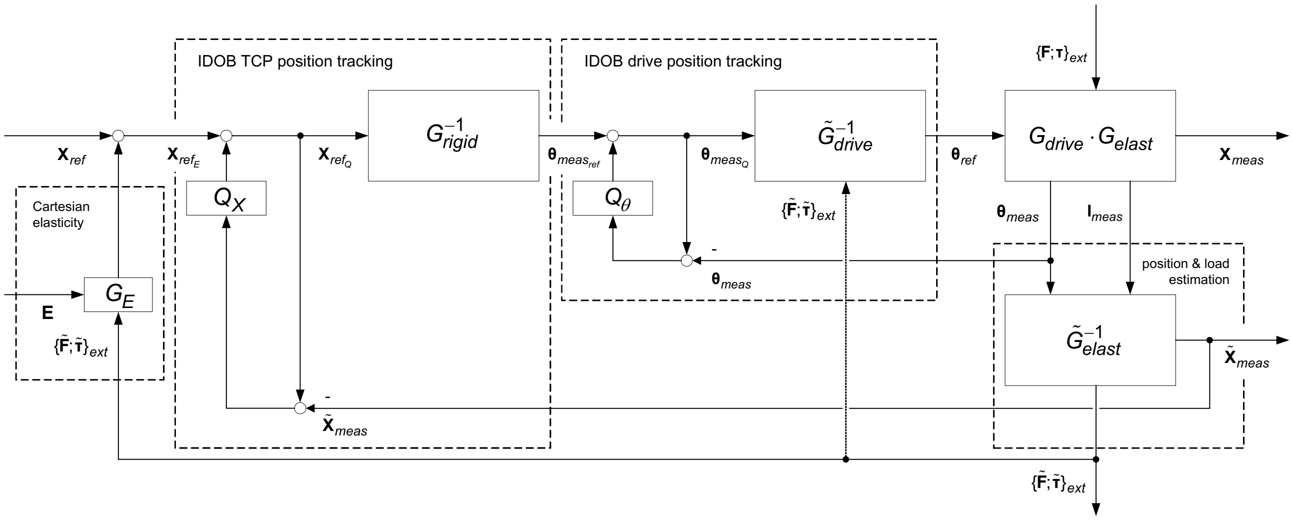

Figure 3: Cascaded control scheme of a PKM

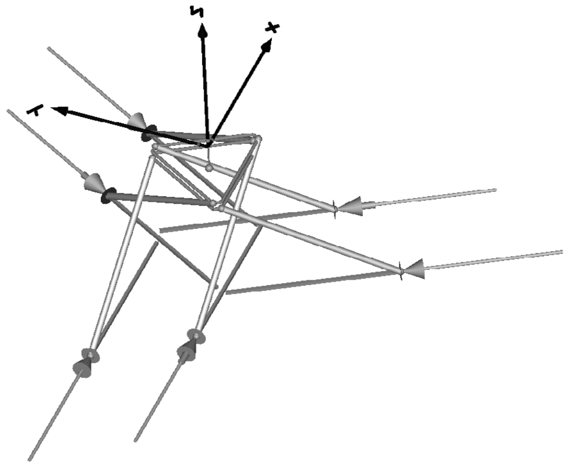

Figure 4: PKM model visualization.

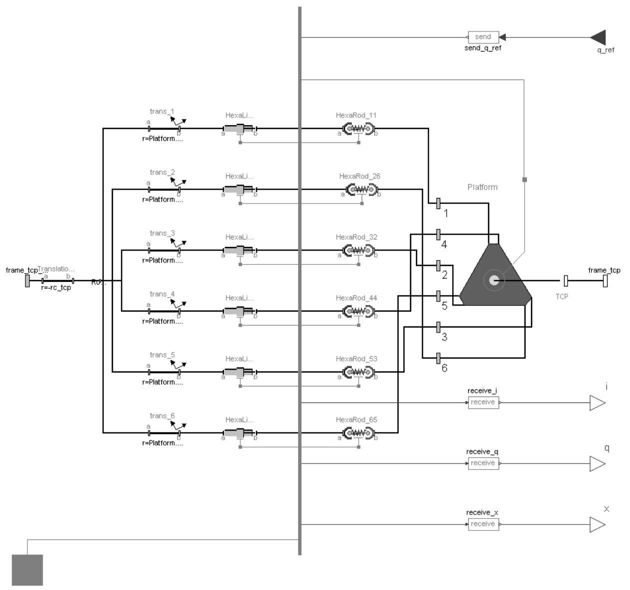

Figure 5: PKM overall model.

of such a system by means of Dymola offers now an easy way to do that. The overall model $\mathbf{G}_{drive} \cdot \mathbf{G}_{elast}$ (Fig. 5) is able to simulate the six linear drives including their friction effects and integrated controllers as well as the physical layout in a simplified structure of struts, which are represented as one-dimensional spring-damper-systems with mass-point. For this, many standard models of the Modelica library and a few own special models are used. Input signals of this element are the reference trajectories of the drive controllers and the perturbing load, output signals are the measurable drive position and force and the actual cartesian TCP position. The control structure has now to be completed with inverted and semi-inverted versions of the overall model.

4 Derivation of Inverse and Semi-Inverse Models

As described above the overall model has to be inverted in different variations. For this, we only have added some `TwoInputs` / `TwoOuputs` - blocks to the input and output connectors of the overall model, but nothing else (Fig. 6) The Modelica translator derives signal directions on it's own [4, 5].

In some cases these changes lead to problems because often derivatives of some expressions are necessary, which can't be differentiated e.g. in case of the direction dependent static friction. In respect of velocity v there is a not derivable discon-

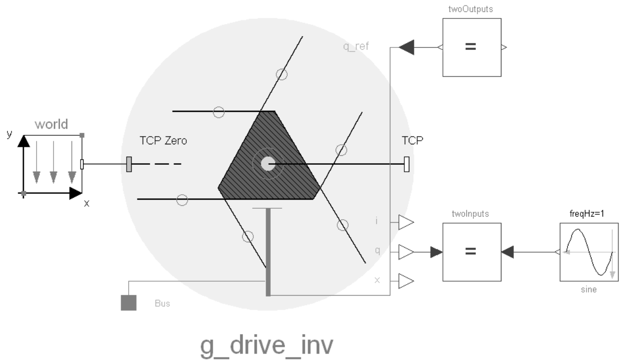

Figure 6: Inversion example of the overall model.

tinuity of Coulomb friction at $v = 0$ m/s which is problematic during model inversion. The solution is to filter the friction force signal. This filter is implemented as series of n first order filters with a overall characteristic of critical damping. Thus the force-signal can be differentiated n times (see `Modelica.Blocks.Continuous.Critical Damping`-Block). Of course the signal is being smoothed and is shaped like a hysteresis, but this can be neglected with a adequately high cut-off filter frequency.

Three variants of the inverted model (Fig. 2) are utilized as follows. For use in outer IDOB a rigid version $\mathbf{G}^{-1}_{rigid}$ is generated, which only transforms the coordinates from Cartesian space to axis configurations space. This system is based on a PKM model, where simply no dynamic effects will be mentioned.

The inner IDOB loop uses a more detailed inverse model $\widetilde{\mathbf{G}}^{-1}_{drive}$ which is intended for drive position tracking. As described later, the whole drive internal controller structure, its friction effects and additional the coupling between the drives and therewith upcoming position dependent loads are mentioned.

Last but not least the TCP position and load estimation model $\widetilde{\mathbf{G}}^{-1}_{elast}$ has been derived. Measured drive positions and currents enable this variant to estimate a actual TCP position and perturbing loads (force / torque). Unfortunately using current as drive load indicator is not appropriately. If the static (Coulomb) friction force is higher than the required drives force in hold-up position, the model is not able to determine the machine load, because the drive will not try to move in this case and no current is necessary to keep position. So it's recommended to use a more sensible measuring signal (of virtual sensors), but the concept remains the same. This inversion variant is primary used to register the elastic effects of the machine structure and to provide an in reality not or not easy to measure TCP position signal. A secondary advantage is that this model can be used as source to apply homogeneous compliance at the TCP, which relies on this force / torque measurements. As consequence we can establish a respective sensitive tool.

5 IDOB drive position tracking

During the development of the complete DYMOLA implementation, realization of executable systems has shown to be a remarkable challenge. In a first step of development the inner IDOB loop had to be realized. As mentioned, the linear drives are working with decentralized encapsulated control by means of cascaded PI-velocity and P-position tracking. Caused by the drive couplings and a changing load, there is no optimal control configuration as for a single axis with fixed load. Hence, the aim is to improve the tracking performance, but only by varying the input signal of the drive controllers using a feedforward element. This is done as in the IDOB architecture by means of an inverse model. Because the model will never match the real linear drives behavior, a feedback loop generates an error minimizing signal.

While all models and their inverse derivatives could be realized quite easily, the multidimensional connection to the intended control structure in one Dymola-model overextended all available compilers. Only in single axis configurations the structure could be verified completely. In this example the performance was improved by multiple decades with a filter cut-off frequency of 1000 Hz. In this case the plant model and the inverted nominal model had very different friction parameters.

The connection of all IDOB elements succeeded only within Simulink by multiple import elements (Fig. 7). However, the performance of this implementation is affected by the required simple fixed step solver and the necessary input filters in all Dymola import elements in order to get the input signals with sufficient order of differentiability. With this environment the inner IDOB was tested by a spacial test trajetory (Fig. 8) and compared with the original control structure and only feedforward control by the inverse model (Fig. 9). As it can be seen from the absolute error values of one axis in figure 9 the tracking errors are reduced with the feedforward model up to 50 %, but with complete IDOB control the errors are lower than 10 % than before. However, on the other side there are considerable spikes, which are resulting from chattering of the non

	Original system	Feedforward control	IDOB control
No perturbative load	100 %	75 %	12 %
Perturbative load: 4 kg	101 %	70 %	11 %

Table 1: Relative mean error values.

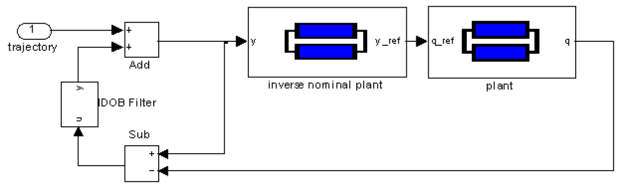

Figure 7: Simulink implementation of the inner IDOB loop.

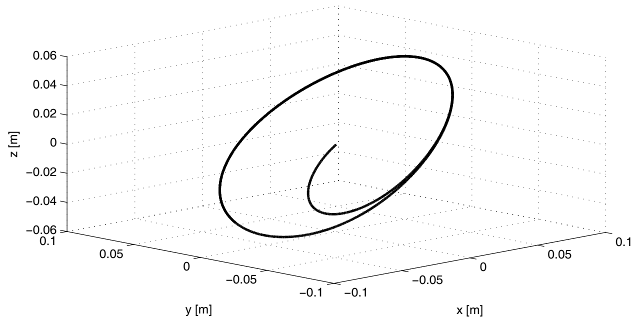

Figure 8: Spacial test trajectory.

ideal friction model in the plant model at velocity zero-crossing . They are also the reason for a quite limited cut-off frequency of the feedback filter at 50 Hz. Table 1 gives the relation of the summarized mean error values of all axes over the test trajectory with respect to the original system. Obviously, the control structure shows also robust behavior in case of added parameter differences between plant and inverse nominal model.

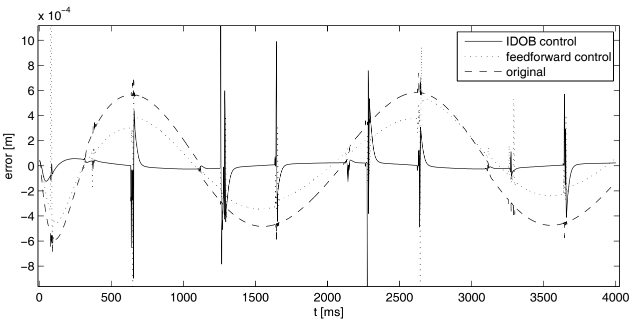

Figure 9: Comparison of tracking errors.

6 Real-time Environment

To control the laboratory machine by this approach, we need to involve the derived models in a real-time environment. In this case MATLAB-xPC-Target is chosen, because it is more easy to integrate a Dymola model into Simulink with xPC-Target real-time extension. In a capable model, which can be downloaded on a xPC-Target machine, the overall plant model $\mathbf{G}_{drive} \cdot \mathbf{G}_{elast}$ is replaced by connections to the drive controllers of the machine by a SERCOS-interface (signals on left and bottom side). To be able to use the SERCOS bus from xPC-Target, a appropriate Simulink block was created [6]. The integration of a Dymola model in a Simulink model is possible with the interface block provided by Dymola itself. With some options one is able to compile and link the Simulink model with the Dymola model translated by the Dymola translator for a PC-based target.
In order to calculate the complex cascaded control structure with its different models it is necessary to use a high performance target machine. Because of real-time purposes also here the model must be calculated with a fixed step solver. Hence with Dymola one have to chose the Euler algorithm (if necessary with inline integration). This fact implies that the calculation does not converge as good as a variable step solver would do. However, complete test of cascaded IDOB architecture is still in future work, where the potentials of real-time optimization have to be developed.

7 Conclusion

This paper presents first practical results of controlling a laboratory PKM by the approach of IDOB control. It could be shown, that on the way of generating real-time simulations Dymola is not only an analysis tool but moreover can be used for powerful control design and target code generation. While the main domain of such processing is multi-axis control, further improvements are required in the solution process of tasks with such high complexity.

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