CONTROL RAPID PROTOTYPING OF REDUNDANTLY ACTUATED PARALLEL KINEMATICAL MACHINE

Michael Valášek, Zbyněk Šika, Jan Zavřel, Tomáš Skopec, Pavel Steinbauer

CTU in Prague, Faculty of Mechanical Engineering

Abstract

Redundantly actuated parallel structures can substantially improve all mechanical properties of machine tools. They achieve higher stiffness, eigenfrequencies and accelerations. The workspace is without singularities and ratio between workspace and machine overall space is improved.

Nevertheless the standard control of redundantly actuated machine drives results into mutual fighting of drives. The modified control strategy which removes drive conflicts has been developed and implemented.

This has been demonstrated on the mechanical design and control development of functional model of redundantly actuated parallel kinematical machine tool Sliding Star. The mechanical structure development tools are based on Matlab environment and computational power, the control design and implementation are based on the RAD chain Matlab-Simulink-RealTimeWorkshop-dSpace (RTI and ControlDesk).

1 Introduction

Redundantly actuated parallel structures can substantially improve all mechanical properties of machine tools [1]. They achieve higher stiffness, eigenfrequencies and accelerations. The workspace is without singularities and ratio between workspace and machine overall space is improved.

Nevertheless the standard control of redundantly actuated machine drives results into mutual fighting of drives. The modified control strategy [2] which removes drive conflicts has been developed and implemented.

This has been demonstrated on the mechanical design and control development of functional model of redundantly actuated parallel kinematical machine tool Sliding Star. The mechanical structure development tools are based on Matlab environment and computational power, the control design and implementation are based on the RAD chain Matlab-Simulink-RealTimeWorkshop-dSpace (RTI and ControlDesk).To cover overall mechanical and control design steps, compact tool set of methodologies, algorithms and software has been developed.

2 Sliding Star

The kinematical structures of machine tools have been recently changed from traditional serial ones into parallel ones [1]. The parallel kinematical structures means that the platform (machine tool carrier) is suspended on several links simultaneously (Fig. 1b) in contradiction to serial kinematics with just one link (Fig. 1a). Serial kinematics must move the drives within its structure, the parallel one has all drives on the frame. The main requirements on the machine tools are the high accuracy, high productivity, small space demands and certainly the price. The manufacturers try to accomplish these requirements by machines with high stiffness, high dynamic capabilities, large workspace and to reduce production costs. The achievement of these goals interferes with the long-term conceptual design problems of machine tools. The frame of machine tool is loaded by bending, there are large moving masses in the machine tool construction, the backlashes and inaccuracies in serial kinematical chain are added and the ratio of workspace and machinespace (the overall space occupied by the machine on the shopfloor) should be always minimized. The parallel kinematics concept seemed to overcome all these problems.

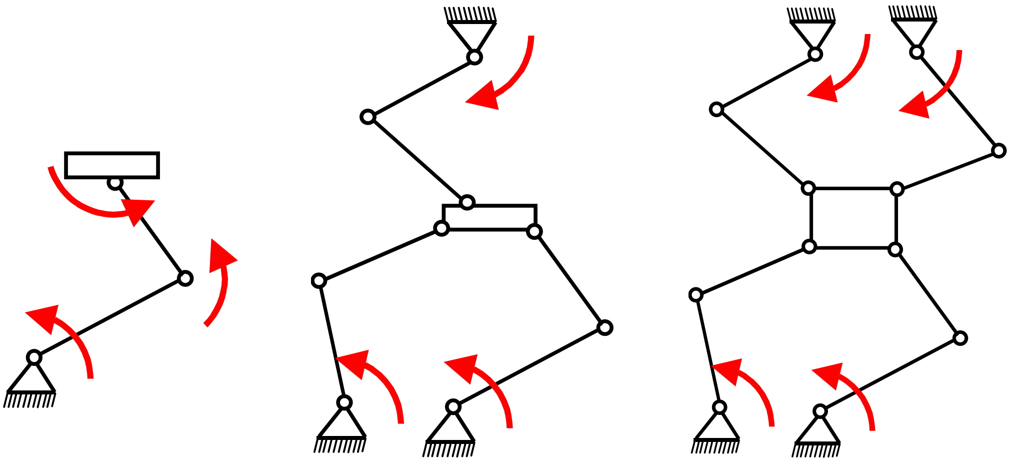


Fig. 1 Kinematical structures

Parallel kinematics is a truss structure and therefore the loading of links is just the stroke/pressure. The remarkable property of parallel kinematics (Fig. 1) is that all drives can be located on the frame and therefore the moving masses are reduced. Both of that improve the mass-stiffness ratio and the resulting accuracy. Besides that the kinematical chains from the frame to the machine tool are shortened that contributes to the improved kinematical accuracy.

Unfortunately the parallel kinematics structures suffer from several severe problems. If some of the links intersect each other then there arise so-called singular positions. In singular positions an additional degree of freedom instantaneously occurs which however results into complete lost of stiffness in this position. As there are more links their mutual collisions happened often than by serial kinematics. Both these facts result into smaller workspace and unfavourable ratio of workspace and machinespace than by serial kinematics.

Besides that parallel kinematics machines have also problems with accuracy. The transformation between the drive coordinates and machine tool (platform) coordinates is nonlinear. The transformation is accomplished by the computer control system. However, its accuracy is dependent on the knowledge of real dimensions of the machine. Even despite very accurate manufacture of machines it is not possible in case of parallel kinematics to use the design dimensions for the nonlinear kinematical transformation in control system. It is necessary to determine the really manufactured dimensions as accurate as possible. In case of parallel kinematics it is not possible to determine the real dimensions by direct measurement therefore these dimensions must be computed from some indirect measurements. It is so-called calibration well known from robotics applied to machine tools. Traditional calibration procedures are based on the simultaneous measurement of tool center position of parallel kinematics machine by an external measurement device and measurement of internal drive positions of parallel kinematics machine. The serial kinematics structures do not have such problems because the links within the serial structure can be calibrated directly and independently from each other.

All these problems and disadvantages of parallel kinematics can be removed by the application of the principle of redundant actuation and the principle of redundant measurement [1].

Redundantly actuated parallel kinematical structures have the potential for significant increase of all mechanical properties of machine tools. During the development of TriJoint 900H (Fig. 2) there have been proposed and investigated about 50 structural variants with several hundreds thousands parametric variants. The important design variants are on Fig. 3. The variants on Fig. 3a,b,d are redundant ones. The variant on Fig. 3c is nonredundant one corresponding to TriJoint. There were found interesting properties of these structures. If the level of dynamic capabilities is the same then the global stiffness of these structures (Fig. 3a : Fig. 3b : Fig. 3c : Fig. 3d) is approximately in the ratio 0.75 : 2.4 : 2.0 : 3.0 where 100% corresponds to stiffness of good traditional machine tool (about 60 N/μm). The stiffness of the variant on Fig. 3a is surprisingly low and compared to it the stiffness of the variant on Fig. 3d is high [2].

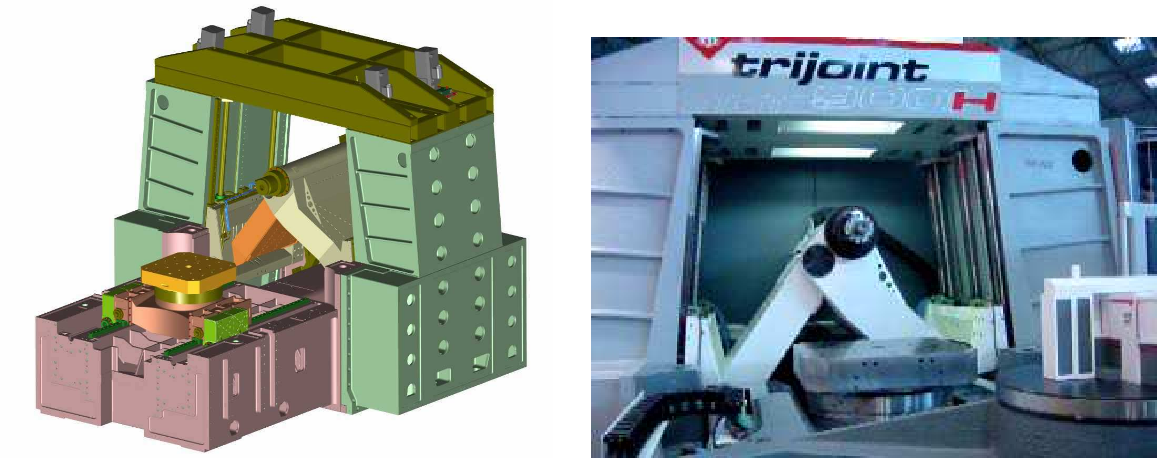
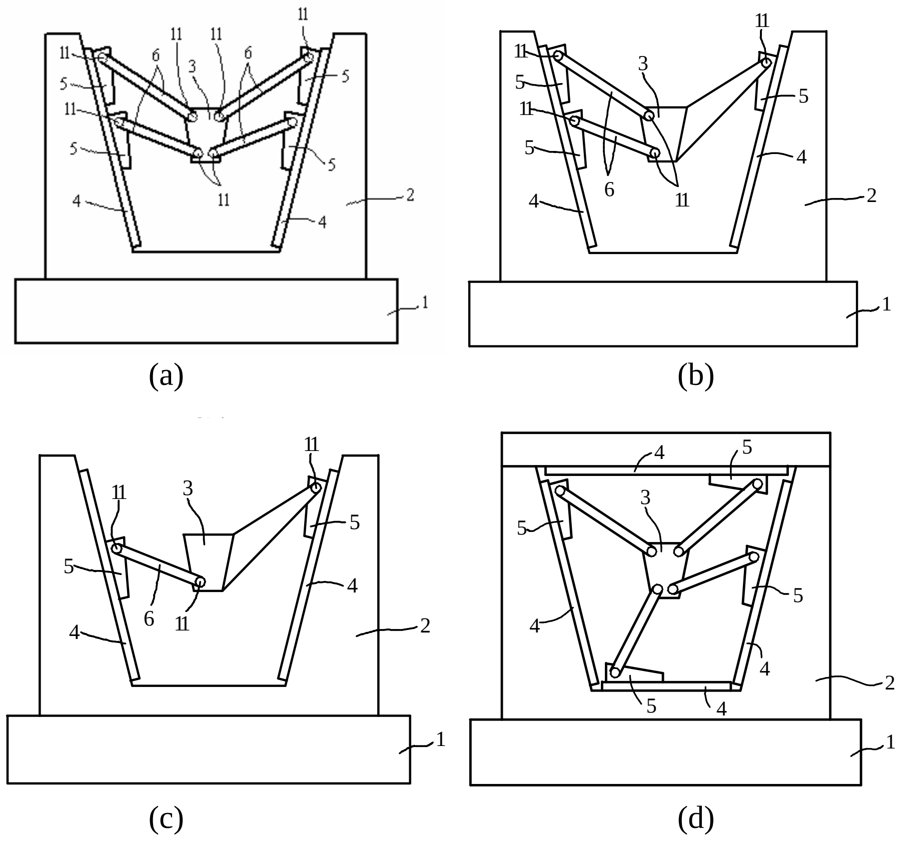


Figure 2 TriJoint 900H



(a) (b)

(c) (d)

Figure 3 Design variants from TriJoint development

The stiffness of the variant on Fig. 3d is significantly high, but its workspace is limited. The further structural modifications resulted into the variant of Sliding Star on Fig. 4 [2]. Its interesting potential is as horizontal machine tool for long profiles with stiffness and dynamics of machine tools with smaller workspace or as portal machine tool for complex large workpieces (Fig. 5).

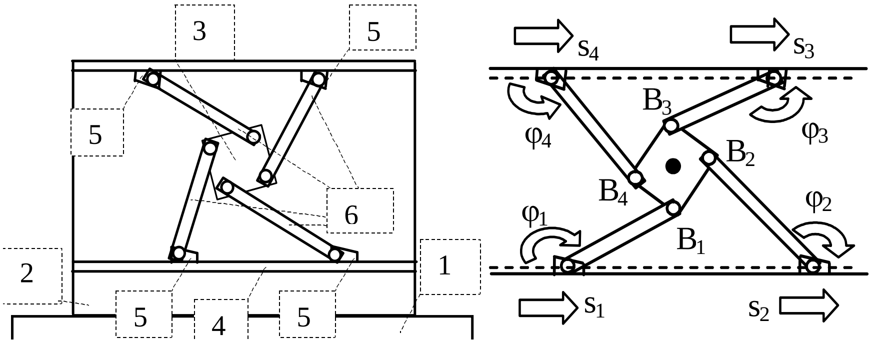


Figure 4 Kinematic scheme and kinematical structure of Sliding Star

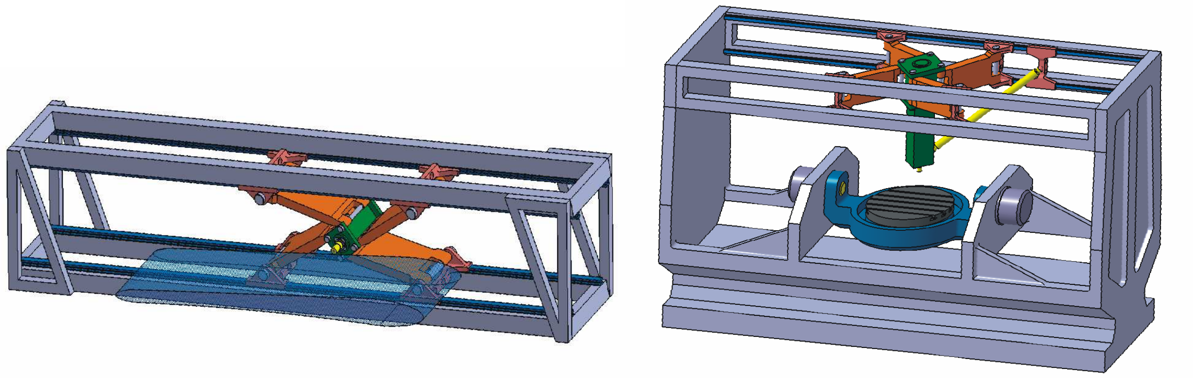


Figure 5 Potential of Sliding Star as horizontal machine center for long profiles or portal machine center for large workpieces

The dimensions of Sliding Star have been intensively optimized. The resulting functional model is on Fig. 6. It is redundantly actuated parallel kinematical structure, i.e. it has more actuarors than DOFs. It has 3 DOFs and 4 actuators on two sliders. The four carriages s_1, s_2, s_3, s_4 are actuated by linear drives and the platform $B_1B_2B_3B_4$ is moved to the desired position.

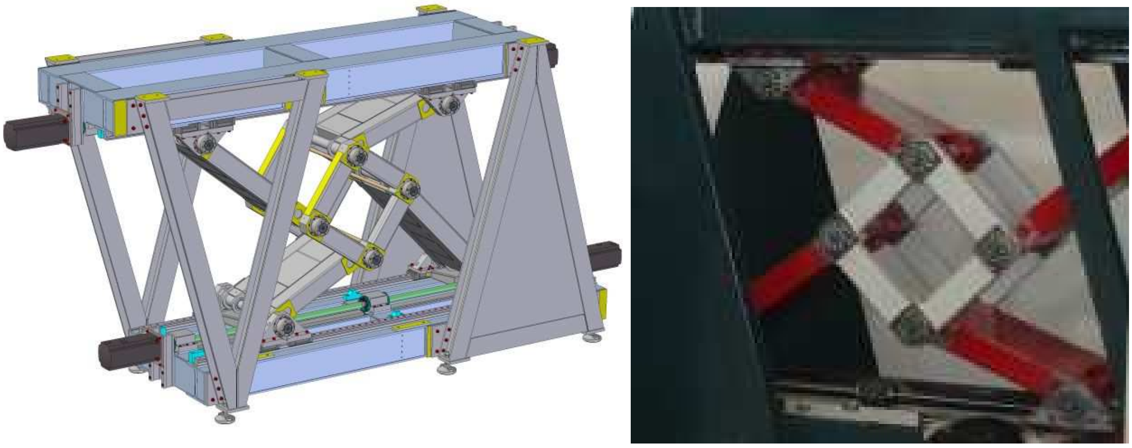


Figure 6 3D model of Sliding Star

The challenge of machine tool with 5 g, 200 N/□m, 150 Hz in whole workspace 1 m3 with on-line measurement and compensation of thermal deformation during machine operation. Such parameters are 3-4 times higher than the parameters of current machine tools. Its concept maybe similar to Sliding Star.

3 Control of redundantly actuated structures

One of the critical problems of redundantly actuated kinematics is the control. There is a danger of mutual fighting of redundant actuators due to always existing difference between reality and its kinematical model (e.g. Fig. 7). There have been developed modified control approaches that eliminate these problems [2].

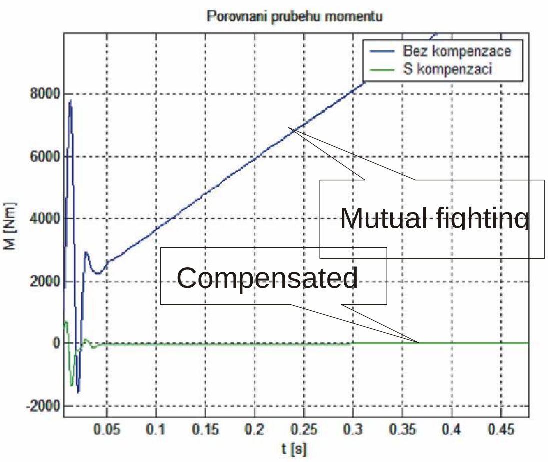


Figure 7 Conflict of redundant actuators and its compensation

The dynamics of parallel kinematic structure is conveniently described by Lagrange's equations of mixed type

$$\begin{aligned} &\mathbf{M}\ddot{\mathbf{s}} - \mathbf{\Phi}_s^T \boldsymbol{\lambda} = \mathbf{g} + \mathbf{T}\mathbf{u} \\ &\mathbf{f}(\mathbf{s}(t)) = \mathbf{0} \end{aligned} \tag{1}$$

where **M** is a mass matrix, **s** is a vector of physical coordinates (their number is higher than the number of DOFs), which are constraint by kinematic constraints $\mathbf{f}(\mathbf{s}(t)) = \mathbf{0}$, $\mathbf{\Phi}_\mathbf{s}$ is Jacobian of these constraints, $\boldsymbol{\lambda}$ is a vector of corresponding Lagrange's multipliers, **g** is a vector of dynamic and applied forces, matrix $\mathbf{T}$ transforms the inputs **u** (*n* torques) into *n* drives.

The physical coordinates **s** consist of the independent coordinates **x** (conveniently Cartesian and orientation coordinates of the platform), drives' (actuators') coordinates $\boldsymbol{\varphi}$ and other auxiliary geometrical coordinates **q**.

These equations of motion can be transformed into independent coordinates **x** using the null space **R** of the Jacobian $\mathbf{\Phi}_\mathbf{s}$ which describes the relation between physical and independent coordinates $\dot{\mathbf{s}} = \mathbf{R}\dot{\mathbf{x}}$

$$\mathbf{R}^T\mathbf{M}\mathbf{R}\ddot{\mathbf{x}} + \mathbf{R}^T\mathbf{M}\dot{\mathbf{R}}\dot{\mathbf{x}} = \mathbf{R}^T\mathbf{g} + \mathbf{R}^T\mathbf{T}\mathbf{u} \tag{2}$$

Among the considered coordinates **s** there are important the coordinates of the drives $\boldsymbol{\varphi}$ and the independent coordinates of the platform **x**. There is the mapping from independent coordinates to the coordinates of drives

$$\boldsymbol{\varphi} = \boldsymbol{\varphi}(\mathbf{x}) \tag{3}$$

$$\dot{\boldsymbol{\varphi}} = \frac{d\boldsymbol{\varphi}}{d\mathbf{x}}\dot{\mathbf{x}} = \mathbf{J}\dot{\mathbf{x}} \tag{4}$$

The force interaction of the platform of kinematic structure with the environment can be described by the forces **F** acting on the platform (they are acting on the independent coordinates **x**) and by the drive torques **n** (they are acting on the coordinates of drives **φ**). Their mutual relation is

$$\mathbf{F} = \mathbf{J}^T\mathbf{n} \tag{5}$$

If the traditional approach of cascade PID controllers on position, velocity and current level is applied there is the serious problem of mutual fighting of redundant actuators. It is due to the fact that the kinematic model of the redundant parallel structure is never perfect. Due to the redundancy of drives there is no one-to-one mapping from coordinates of drives **φ** to independent coordinates **x** (inverse of (3)). The dependence of redundant coordinates of drives on independent coordinates represents a constraint among the drive coordinates (3).

This means that the drive coordinates **φ** are dependent. This constraint is in reality not satisfied due to the imperfection of kinematic model and PID controller tries to achieve zero errors for all dependent drive coordinates **φ**. It is not possible and the result is the increase of drive torques up to the saturation. Such behavior was achieved by both simulation and laboratory experiments on laboratory model of redundant parallel structure.

3.1 Decentralized (Local) Control

In order to solve this problem there have been developed the following modification of traditional cascade drive control. In fact it is decentralized (local) control of drives. The proposed control scheme is on Fig. 8. The only modification is the block of transformation. Its idea is that the local decentralized controllers compute the desired drive torques $\mathbf{n}_d$. From them the desired resulting forces $\mathbf{F}_d$ acting on the platform can be computed

$$\mathbf{F}_d = \mathbf{J}^T\mathbf{n}_d \tag{6}$$

Now the applied drive torques **n** are to be determined from underdetermined system of linear equations

$$\mathbf{J}^T\mathbf{n} = \mathbf{F}_d \tag{7}$$

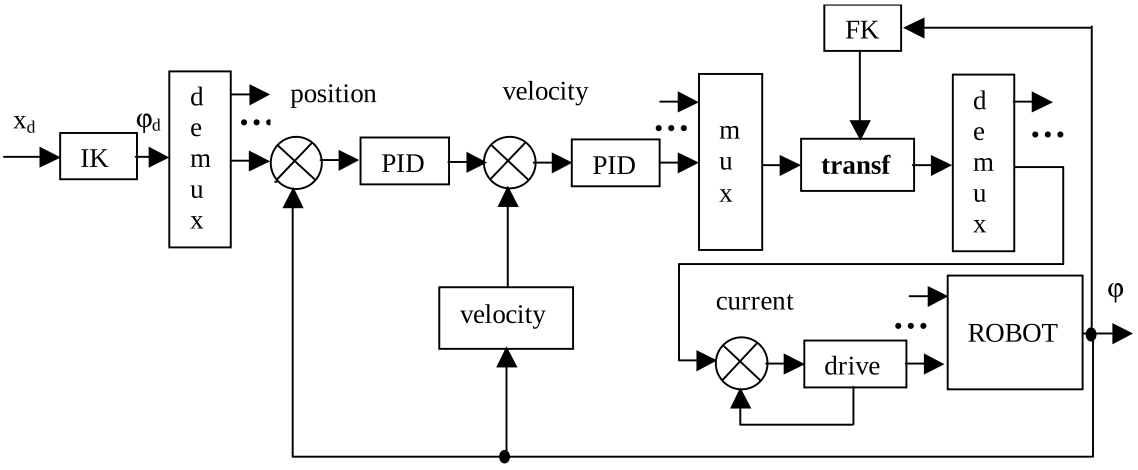


Figure 8 Control scheme of modified decentralized control (IK=inverse kinematics, FK=forward kinematics)

The solution of this problem which minimizes the values of **n** is

$$\mathbf{n} = \mathbf{J}(\mathbf{J}^T\mathbf{J})^{-1}\mathbf{J}^T\mathbf{n}_d \tag{8}$$

The simulation of this scheme has proved that the problems of redundant drive fighting is removed. Nevertheless the scheme has been implemented in simplified form on the laboratory model of Sliding Star only on the integral component of the controller (Fig. 9). The practical experiments have shown full applicability of this approach.

A special development was devoted for the on-line solution of forward kinematics of redundant parallel kinematic structures. The approach of differential kinematics being on-line integrated was successfully applied.

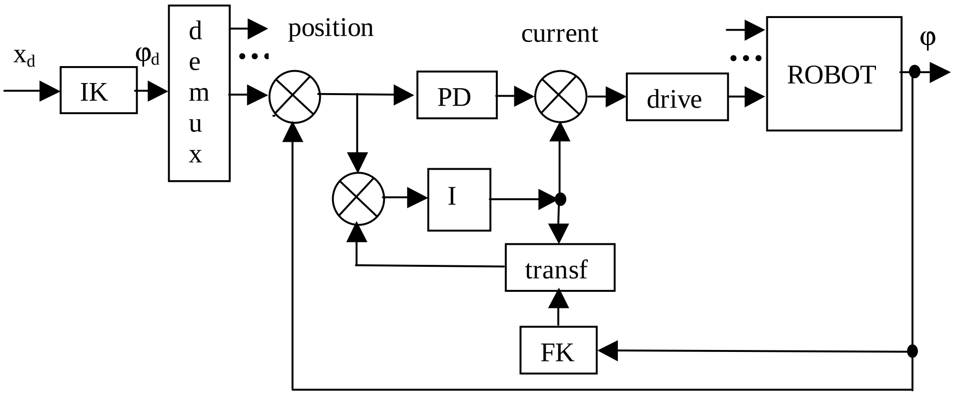


Figure 9 Implemented control scheme of modified decentralized control

3.2 Centralized (Global) Control

The problem of control of redundant parallel kinematic structures is the interaction among parts and redundant actuator of the parallel kinematics which are not independent. The general solution of this problem is to control the structure from the centralized (global) point of view where the interactions can be directly taken into account.

The simplest control approach is to apply PID controller however on the global level. The corresponding control scheme is on Fig. 10. The approach is based on the control of the independent Cartesian and orientation coordinates **x** of the platform on level of positions and velocities. The result of these blocks is a fictitious control force **F** acting directly on the platform. This force must be transformed into local drive torques **n** according to the solution of (6). Taking into account the solution with minimum values the result of the transformation is

$$\mathbf{n} = \mathbf{J}(\mathbf{J}^T\mathbf{J})^{-1}\mathbf{F} \tag{9}$$

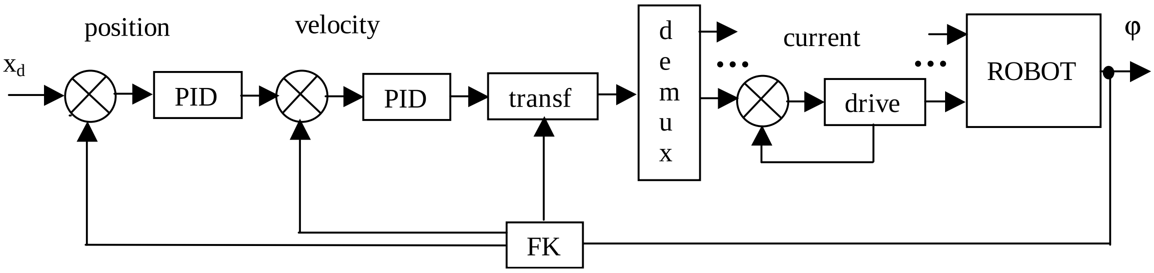


Figure 10 Control scheme of centralized control (FK=forward kinematics)

4 Control Implementation

The objective of the research on this functional model of Sliding Star with properties of real machine tool and industrial control system has been to demonstrate the ability to control redundantly actuated (overdetermined) parallel kinematical structures and to verify the new possibilities of calibration coming from redundant measurements.

Traditional control fails for redundant actuation and non-redundant calibration requires external artefact-etalon and does not enable the calibration during machine operation.

The ultimate objective is to implement the control of redundantly actuated parallel kinematical structure on the industrial control system Siemens 840D using OA Packet enabling to modify the original control software. It has not been possible within the time period until IMT 2006 exhibition. Therefore the intermediate way of implementation has been selected. It consists of velocity controllers of all drives in Siemens control system Simodrive for local drive control and of position/trajectory generator and position controller in DSP 1103 of dSpace.

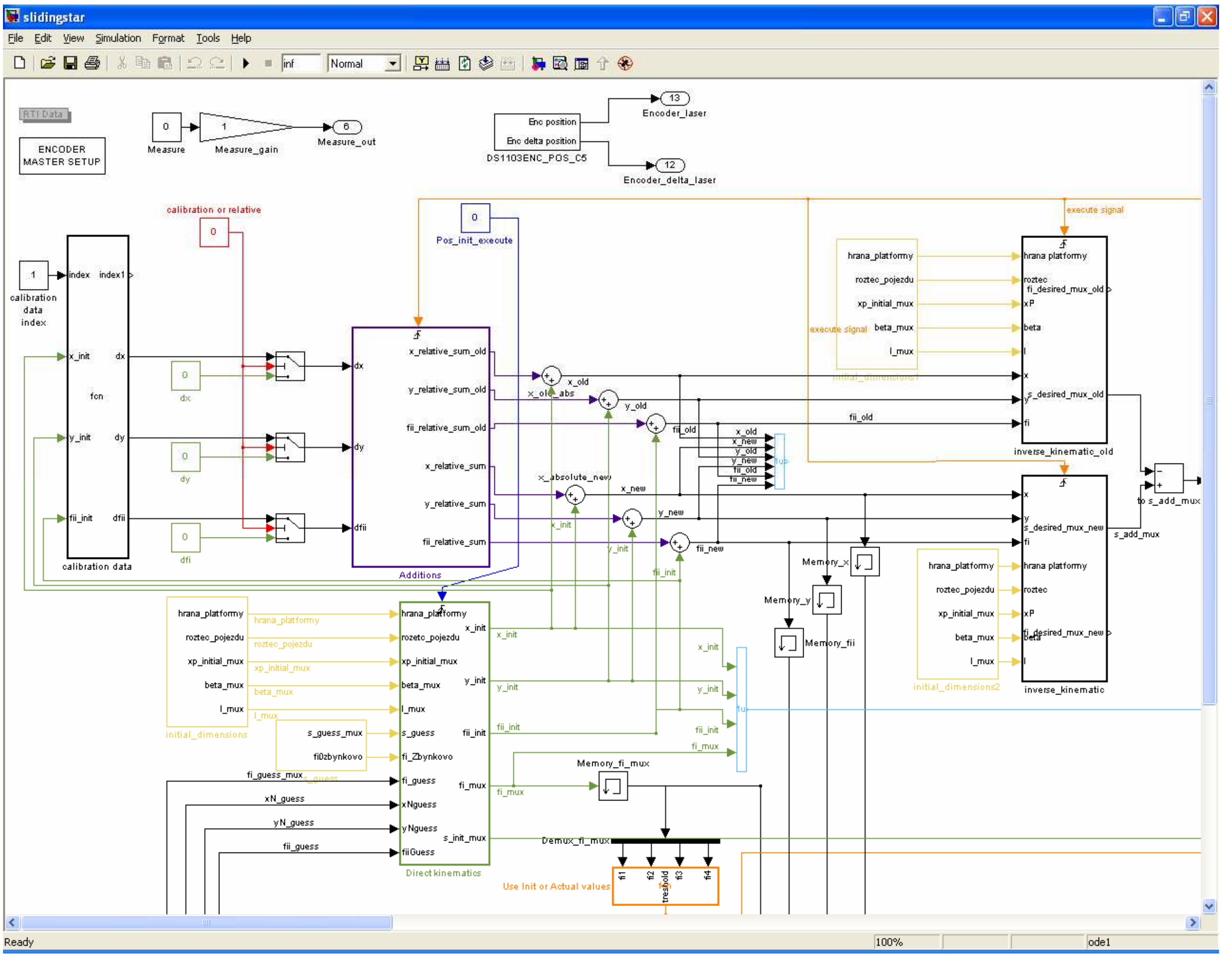
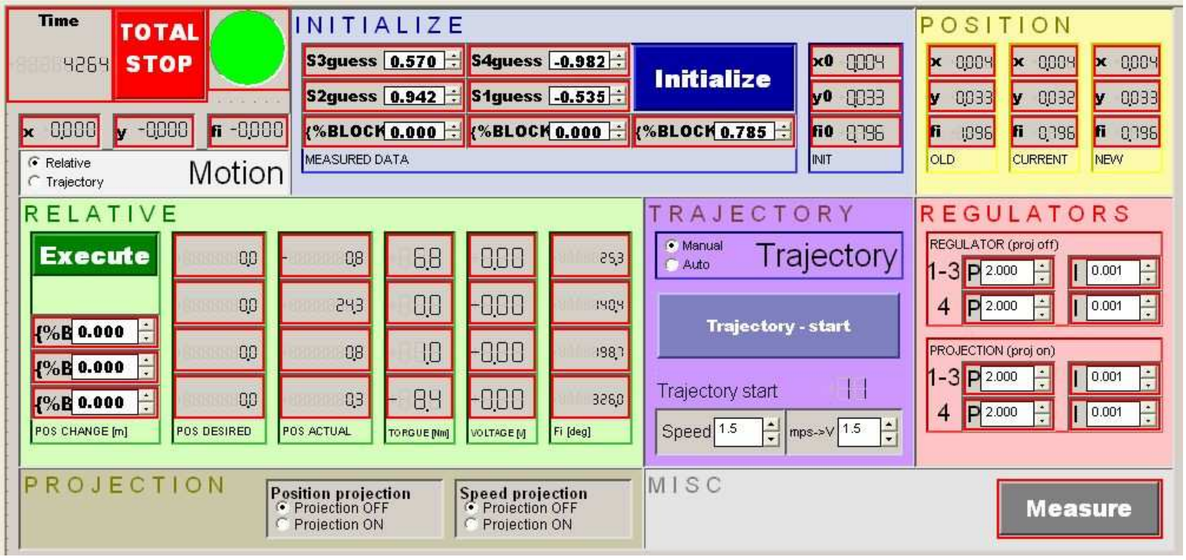


Figure 11 Control scheme in Simulink

Complex control software has been developed using control software rapid development chain Matlab-Simulink-RealTimeWorkshop-dSpace. It was necessary to develop many modules. They have covered the inverse and direct kinematical transformations, the generation of desired trajectory, position controller with compensation from Fig. 9, velocity controller with compensation equivalent to Fig. 8, controller for elementary Cartesian motions, controller of generated trajectories, protecting of emergency states, etc. The part of control scheme in Simulink is on Fig. 11. The result was a list of software modules:

Speed PI, Position PI, Ramp Movement generator, Forward Kinematics (newton), Inverse Kinematics, Trajectory Generation, Trajectory Execution, Trajectory Repeater, Trajectory Speed, size Adjustment, Decentralized Speed Control, Decentralized Position Control, Communication with Siemens Simodrive, Incremental Sensor Communication, GUI, 3-axis incremental movement of working platform.

The development of such demanding control software package has been heavily supported and accelerated by the capabilities of control software rapid development system Matlab – dSpace. The interface Control Desk of dSpace DSP 1103 has enabled to create a customized interface for easy operation of control system. Its GUI is on Fig. 12. The lesson learned is again the fact that without the control software rapid development system Matlab – dSpace the task cannot be completed within the short time period of 2 months.



Time 4264

x 0.000 y -0.000 fi -0.000

● Relative
○ Trajectory

S3guess 0.570
S4guess -0.982
S2guess 0.942
S1guess -0.535
{%BLOCK 0.000
{%BLOCK 0.000
{%BLOCK 0.785

x0 0.004
y0 0.033
fi0 0.796
INIT

	OLD	CURRENT	NEW
x	0.004	0.004	0.004
y	0.033	0.032	0.033
fi	1.096	0.796	0.796

POS CHANGE [m]	POS DESIRED	POS ACTUAL	TORGUE [Nm]	VOLTAGE [V]	Fi [deg]
	0.0	-0.8	6.8	0.00	25.3
{%B 0.000	0.0	24.3	0.0	-0.00	140.9
{%B 0.000	0.0	0.8	1.0	-0.00	198.7
{%B 0.000	0.0	0.3	-8.4	-0.00	326.0

● Manual
○ Auto

Speed 1.5 mps->V 1.5

REGULATOR (proj off)
1-3 P 2.000 I 0.001
4 P 2.000 I 0.001

PROJECTION (proj on)
1-3 P 2.000 I 0.001
4 P 2.000 I 0.001

Position projection
● Projection OFF
○ Projection ON

Speed projection
● Projection OFF
○ Projection ON

Figure 12 Sliding Star Control GUI

5 Results

The real size functional model Sliding Star including control system based on Siemens 840D has been built and successfully shown at IMT 2006 exhibition in Brno 2006 (Fig. 13). The functional model has demonstrated the capability to develop and especially to control the redundantly actuated parallel kinematical structures. The usage of this technology is ready for industrial applications.

6 Conclusions

The paper has described the development of control system of functional model of redundantly actuated parallel kinematical structure Sliding Star. The development has been enabled by the application of control software rapid development system Matlab – dSpace.

References

[1] Valasek, M. et al.: The Innovative Potential of Redundantly Actuated PKM, In: *Proc. of Parallel Kinematics Seminar PKS 04*, IWU FhG, Chemnitz 2004, pp. 365-384

[2] Valášek, M. et al.: Design-by-Optimization and Control of Redundantly Actuated Parallel Kinematics Sliding Star. *Multibody System Dynamics* 2005, vol. 14, no. 3-4, p. 251-267.

Figure 13 Running Sliding Star at IMT 2006 Exhibition

Michael Valášek
Michael.Valasek@fs.cvut.cz