High-Speed Parallel Robots with Integrated Vibration-Suppression for Handling and Assembly

Stephan Algermissen, Michael Rose, Ralf Keimer, Elmar Breitbach

Institute of Structural Mechanics, DLR e.V. (German Aerospace Center), Lilienthalplatz 7, Braunschweig, Germany

ABSTRACT

Automation of handling and assembly, which are complex technological processes, requires qualified solutions. The longterm development goals are decreasing cycle-times and increasing quality of processing. These goals can be achieved by means of innovative concepts based on parallel kinematics which enable higher velocity and acceleration while maintaining at least the same accuracy as compared to conventional systems.

Principally, parallel kinematics are better suited for high accelerations than serial structures because the drive units can be mounted on the frame without the need to move their high masses. Additionally, parallel structures are stiffer than their serial counterparts. Two key features of the innovative concepts introduced in the paper are lightweight structural components which allow to reach even higher accelerations and integrated smart actuators and sensors to control the vibrations induced by the high accelerations.

This paper discusses modelling of parallel kinematics, control-strategies for the vibration suppression, and design-criteria for active rods. These active rods have built-in piezoceramic stacks serving as both sensors and actuators that provide the means to supresss the vibrations. A two-degree-of-freedom parallel structure with active rods is used as test-case and experimental results confirming the potential of smart parallel kinematics are shown. An outlook to the ongoing research in the field of parallel robots is given.

Keywords: Parallel kinematics, vibration suppression, automation, handling and assembly, smart structures, robust control

1. INTRODUCTION

With the increasing requirements in machine speed and accuracy, reduction of structural vibrations becomes more and more important. The vibrations make the process results worse and shorten the lifecycle.[4] Especially the need to reach both contradictory goals of high speed and high accuracy makes Adaptronics necessary to extend the performance level.[5] Good experimental results have already been achieved by introducing an active interface at a high precision form measuring machine.[6] A similar concept has been used in a turning machine tool.[7]

Looking at a high speed flexible parallel robot in a first investigation a redundant drive was successful used to increase the performance.[8] Starting from this point a German DFG collaborative research center 562, consisting of some institutes of the Technical University of Braunschweig and the Institute of Structural Mechanics at DLR, was set up,[9] with the goal of using adaptronic methods to further increase the performance of high speed parallel robots. Two work packages of this project will be described in this paper. On the one hand the design of a demonstrator including adaptive measures and on the other hand simulation and control. For the modelling, the multibody simulation programm SIMPACK[10] is used. This commercial multibody simulation code is highly developed to consider the deformations of flexible bodies in the simulation.[11] This offers potentialities to simulate flexible bodies with distributed actuators and sensors as needed for the adaptronic design process.[12] Also the kinematical and dynamical equations of motion which are necessary for enhanced control concepts shall be generated in an efficient way.

Further Author Information: Send Correspondence to Stephan Algermissen
E-mail: Stephan.Algermissen@dlr.de, Telephone: +49 531 295 2347

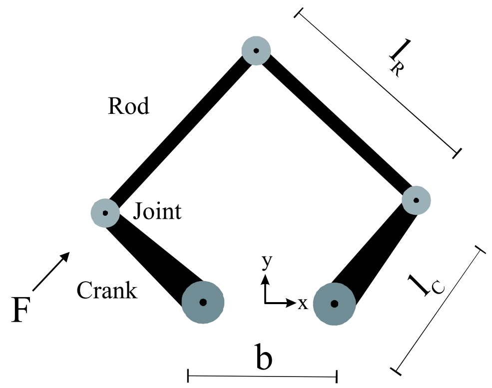

Figure 1. Main dimensions of the demonstrator

Table 1. Data of the demonstrator

Name	Description	Value
b	Distance between axes of motors	300 mm
l_C	Distance between axes of crank-joint and axes of motors	300 mm
l_R	Distance between joints of a rod	500 mm
F	Force in direction of rod	approx. 230 N
M	Maximal Torque of Direct-Drive	70 Nm
I_M	Moment of Inertia of Direct-Drive	0.036 kg m^2

2. REALIZATION

2.1. Rough design

For first tests of adaptive measures a five-joint structure is planned. The demonstrator will initially be a robot with two degrees of freedom x,y. For further tests regarding robot-control an effector will be applied, giving extra degrees of freedom (e.g. rotary motion around z, or movement in z direction). In order to avoid the need to stiffen the structure in z direction a vertical configuration is chosen.

The goal of the demonstrator is to reach accelerations of 10g to 20g at the effector. With the given direct-drive-motor this just can be achieved by limiting the mass of the structure. Regarding the accelerations the pose in figure 1 is worst-case and the maximum acceleration is given by equation:

$$a_{\text{max}} = \frac{{}^{M}\!/_{l_C}}{{}^{l_M}\!/_{l_C^2} + m_{\text{joints}} + m_{\text{rod}} + m_{\text{effector}}} = \frac{233\text{N}}{0.4\text{kg} + m} \tag{1}$$

Equation (1) yields to the result that the mass of the demonstrator must be limited to 2 kg or below. As device for embedding adaptive measures an active rod is chosen. Using the main dimensions shown in figure 1 and table 1 the demonstrator is designed. The assembled demonstrator is shown in figure 2.

2.2. Lightweight crank

The crank consists of two CFRP panels, see figure 3. The manufacturing is done by using a mould in which carbon-fiber fabrics is placed. The fiber-filaments are oriented in 45°/45° regarding to the joint to joint axis of the crank in order to bear the shear in the panel. To get a high bending-stiffness in direction of the motion, a belt of unidirectional carbon-fiber is winded.

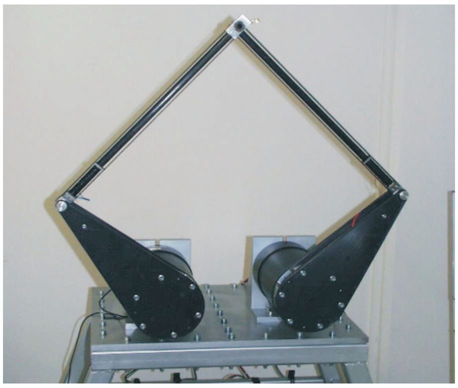

Figure 2. Picture of the demonstrator

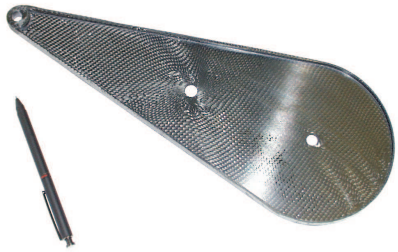

Figure 3. CFRP panel

2.3. Active rod

The active rod for the demonstrator is designed with the possibility for changing parameters in mind, so that it can be used in other parallel-robots. The active rod is at the same time actuator and sensor. This is done by using a piezoceramic stack actuator with one layer connected as sensor. It is well known that the piezostack as a ceramic component is not able to bear tensile loads, thus arising the need for mechanical prestressing the actuator. There are five functional parts to the active rod, which are exchangeable in a modular way, see figure 4:

1. the connectors are housing the joint-bearings,
2. the piezostack is actuator and sensor (stiffness c_a, free stroke l_0)
3. the rod is a tube of unidirectional carbon-fiber (stiffness c_r) transmitting the stroke from the actuator to the connectors
4. the belt is built of unidirectional carbon-fiber (stiffness c_p) and provides the stiffness for prestressing the actuator,
5. the mechanism for prestressing.

The stroke x_2 of the active rod is dependent on the stiffness and the free stroke of the actuator and is given by equation:

$$x_2 = \frac{c_a c_r l_0}{c_p c_r + c_a c_r + c_a c_p} \tag{2}$$

By changing the stiffness (through changing cross-sections of belt, rod or actuator) and changing the length of the actuator (thus changing the free stroke) the weight and the stroke of the complete active rod is determined. In order to obtain the best ratio between stroke and weight an optimization is done.

3. SIMULATION

In order to get a usable model of the five-joint gear, we have to consider, which software we will use to obtain suitable results. There are some possibilities, which we will discuss now.

Direct modelling with lagrange equations or principles of virtual work This method is quite good to obtain direct equations of motion for rigid body systems with simple joints. Though our robotic platform has only revolute joints, the elasticity of the cranks and rods complicates the resulting equations and

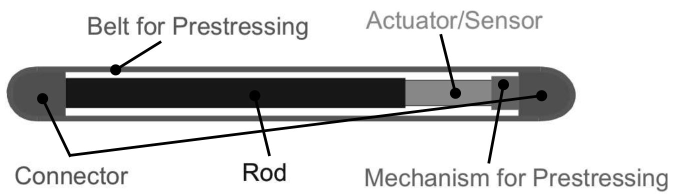

Figure 4. Principle active rod

changes in the model become very time consuming. For some systems however, such a direct approach can be used to avoid algebraic constraint equations. This is especially possible for the five-joint gear, and the dynamical equations of motion are give by a proper state space model. The principal procedure to obtain the equations of motions is given in.[12]

Using a multi body simulation program The use of a multi body simulation system, which can also deal with elasticities, is very promising to get quick models. But the export facilities of such software products has to be examined carefully, if the model itself has to be embedded in other environments. The use of absolute or relative coordinates is also of some importance for the size of the created underlying differential system. If the equations are exported as FORTRAN-code for example, the dynamic system can be solved numerically, but the understanding of the system is greatly reduced. Incidentally, the automatic generation of models with closed kinematic loops leads to differential algebraic equations of motion. The additional constrained equations must be solved with iterative procedures, which is unacceptable for real time applications. However this approach can very well be used to obtain linearized state space models of the robot on a grid in the workspace, which can be used to create an interpolating control strategy.[14]

Hybrid approach To combine the advantages of both methods, we can use the exported model of the multibody-system, but substitute the generated constraint equations by explicit equations, derived from a direct modelling approach. This avoids the iterative solution of implicit constrained equations, but is only applicable in certain applications. This approach is in detail described in.[13] There a C++ coded S-function for MATLAB/SIMULINK is created, which uses the same elastic data as a corresponding SIMPACK model of the five-joint structure, but with hand-coded kinematic equations.

The crucial point for elastic body systems lies in the selection of the representative body deformations which restrict the way, a single body can be streched, bended of otherwise deformed. To limit the number of elastic states to four, the in-plane bending of the cranks and the axial stretching of the rods have been considered in the simulation studies done so far. They show very promising results for the vibration suppression of the five-joint manipulator vibrations, despite the fact, that the out of plane bending of the planar structure has not been considered yet. Simulation is used here only as a test base to study control algorithms. As described later, the implemented real time control is based on system identification.

4. CONTROL

The control design for the demonstrator is divided into two tasks:

Robot control The task of the robot control is to move the effector into a desired position within the workspace using the Direct-Drives (position control). Each element of the demonstrator is treated as a rigid body.

Structural control The task of the structural control is to suppress the vibrations of the effector due to elasticities of the robot and high accelerations during operation.

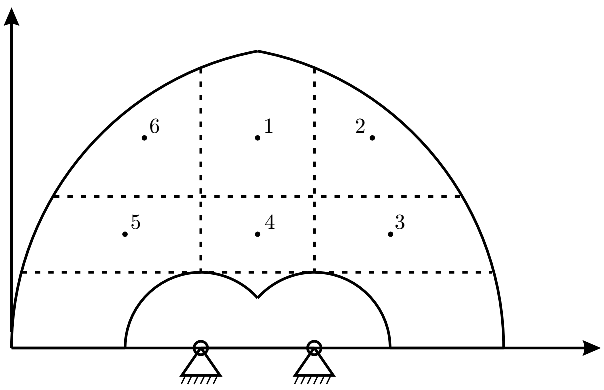

Figure 5. Workspace with operating points

In this article we will focus on the structural control. The robot control is not a subject and is not be mentioned here.

Because of his specific lightweight parallel structure, the demonstrator theoretically can reach shorter cycle times in pick-and-place operations than robots with serial structures. Practically the high accelerations during pick-and-place induce vibrations of the robot structure which lead to dislocation of the effector. The time until the part can be placed will significantly increase. So structural control is essential for an efficient operation.

Previous measurements of the vibration behavior of the demonstrator with a triaxial acceleration sensor at the effector have shown that there exist two dominating modes in the interval from 9 to 12 Hz. In the direction perpendicular to the working space of the robot the amplitudes of these modes reach their maximum. Therefore the acceleration in this direction will be used as plant output.

4.1. Strategy

There are many factors of influence which change the vibration behavior of the robot during operation. The major factors are:

- position of the effector
- mass of the part at the effector
- external disturbances

The only value which is known during runtime is the position of the effector. By introducing a position dependent control, this value is used to increase the performance of the system. The demonstrator operates only in pick-and-place mode and the structural control will be activated shortly before and during the place of the part. Therefore possible problems of switching controllers can disregarded. The two remaining factors the mass at the effector and external disturbances, mentioned above, are simply unknown. Their influence on the plant must be compensated by robust control. The chosen H_∞ control algorithm is able to guaranty the desired robustness.

4.2. Identification

The position dependent control, which has to be designed, cannot provide a controller for every point in the workspace. The vibration behavior of the robot does not change stepwise with the position. Hence a few collected points in the workspace are defined as operating points where a controller will be designed. In a certain neighborhood of these points the same controller will be used. The allocation of the workspace with its 6 operating points is shown in figure 5. For the controller synthesis the transfer matrix between the two piezo actuators, included in the active rods, to the acceleration sensor, which measures the acceleration perpendicular to the working plane, is required. The frequency response function (FRF) from the actuator to the sensor

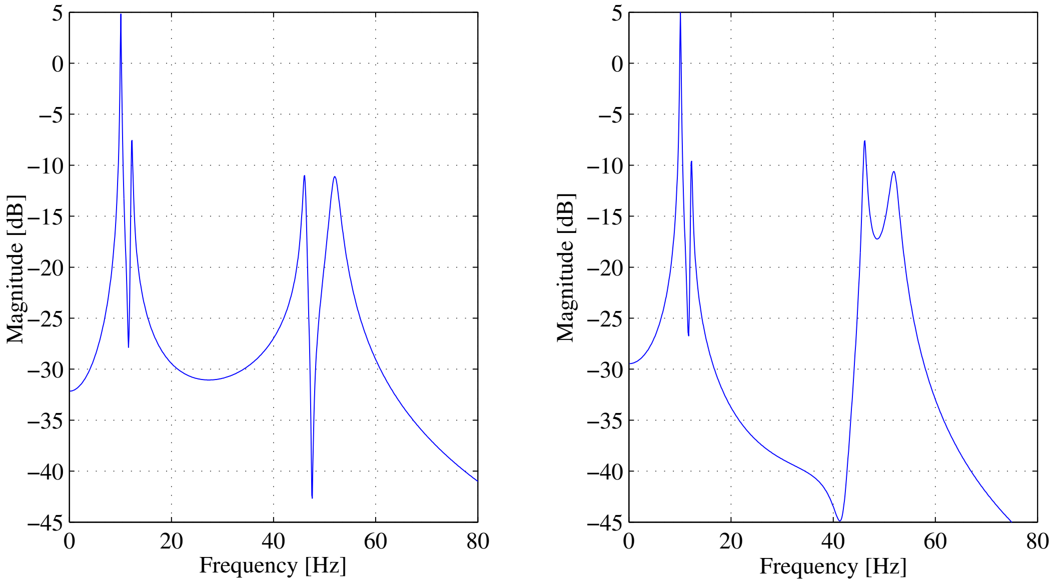

Figure 6. Frequency response function in operating point 1 without additional mass, left: Actuator 1 to sensor, right: Actuator 2 to sensor

Table 2. Eigenfrequencies of the selected modes in operating point 1 without additional mass

Mode No.	Frequency [Hz]
1	9,53
2	12,12
3	45,89
4	51,31

is determined at each working point experimentally to get a model of the reality as exact as possible. The measurements are carried out with an Ono-Sokki FFT analyzer in a frequency interval from 0 till 100 Hz. Three frequency response functions with different mass configurations are recorded per working point to get information about the systems robustness's. The configurations are:

1. without additional mass
2. additional mass of 126 g
3. additional mass of 222 g

For an example of a FRF of the demonstrator in operating point 1 see figure 6. In the measured frequency interval exist four significant modes, see table 2, whose vibrations have to be reduced.

The following system identification of the plant has been carried out with a toolbox for MATLAB, specially developed at the Institute of Structural Mechanics. The toolbox is for the frequency domain and identifies the system in two steps. First, the eigenvalues (natural frequency and damping) of the modes selected before are fit in an iterative process. In the second step the mode shapes in terms of coefficients are assigned by solving an over-determined set of linear equations.

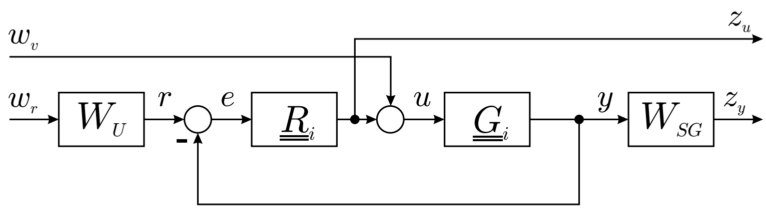

Figure 7. Weighting scheme for the H_∞ controller synthesis

4.3. Synthesis

The synthesis of the controller is done with MATLAB and is based on identified state space models which describe the demonstrator with an additional mass of 126 g at the effector. The models have the form:

$$\dot{\underline{x}} = \underline{\underline{A}}_i\,\underline{x} + \underline{\underline{B}}_i\,\underline{u} \qquad \text{for } i\text{=1..6} \tag{3}$$

$$y = \underline{c}_i^T\,\underline{x}\,. \tag{4}$$

Where u is the voltage of the piezo actuators and y the acceleration of the effector. The transfer matrices $\underline{\underline{G}}_i$ are generated by:

$$\underline{\underline{G}}_i(s) = \underline{c}_i^T\left[\underline{\underline{E}}s - \underline{\underline{A}}_i\right]^{-1}\underline{\underline{B}}_i \tag{5}$$

For the H_∞ controller synthesis, performance specifications in terms of weighting functions have to be formulated. The weighting functions must include all design criterions for the closed loop system. Experiments and experience have shown, that the weighting scheme in figure 7 is very useful for problems of vibration suppression. Expressed in formulas it is:

$$\begin{bmatrix} z_y \\ \underline{z}_u \end{bmatrix} = \begin{bmatrix} W_{SG}\,\underline{\underline{T}}_i\,W_u & W_{SG}\,\underline{\underline{S}}_i\,\underline{\underline{G}}_i \\ \underline{\underline{R}}_i\,\underline{\underline{S}}_i\,W_u & -\underline{\underline{T}}_{u,i} \end{bmatrix}\begin{bmatrix} w_r \\ \underline{w}_v \end{bmatrix} = \underline{\underline{P}}_i\begin{bmatrix} w_r \\ \underline{w}_v \end{bmatrix}. \tag{6}$$

with

Sensitivity:

$$\underline{\underline{S}}_i = \left[\underline{\underline{E}} + \underline{\underline{G}}_i\underline{\underline{R}}_i\right]^{-1} \tag{7}$$

Complementary sensitivity:

$$\underline{\underline{T}}_i = \underline{\underline{G}}_i\underline{\underline{R}}_i\left[\underline{\underline{E}} + \underline{\underline{G}}_i\underline{\underline{R}}_i\right]^{-1} \tag{8}$$

Complementary sensitivity (loop breaking point at u):

$$\underline{\underline{T}}_{u,i} = \underline{\underline{R}}_i\underline{\underline{G}}_i\left[\underline{\underline{E}} + \underline{\underline{R}}_i\underline{\underline{G}}_i\right]^{-1} \tag{9}$$

The transfer matrix $\underline{\underline{S}}_i\,\underline{\underline{G}}_i$ is a measure for the suppression of disturbances and therefore essential for the performance of the control. For the limitation of the control variable, especially out of the bandwidth of the controller, the expression $\underline{\underline{R}}_i\,\underline{\underline{S}}_i$ was included into the weighting scheme. The two complementary sensitivities $\underline{\underline{T}}_i$ and $\underline{\underline{T}}_{u,i}$ are very important for robustness to multiplicative uncertainties at the output respectively the input of the plant. After a few iteration steps useful weighting functions are found, see figure 8. Their inverses are:

$$W_{SG}^{-1}(s) = \frac{0.01s + 0.2\cdot 60\cdot 2\pi}{s + 60\cdot 2\pi} \tag{10}$$

$$W_u^{-1}(s) = \frac{0.01s + 15\cdot 50\cdot 2\pi}{s + 50\cdot 2\pi}. \tag{11}$$

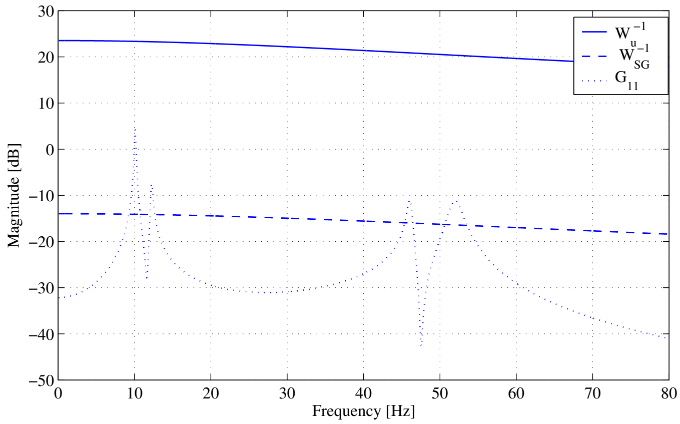

Figure 8. Singular values of the inverse weighting functions

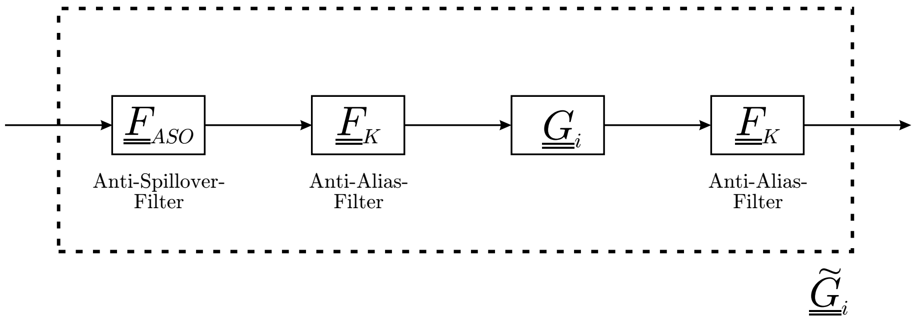

Figure 9. Extended plant $\underline{\underline{\tilde{G}}}_i$

The controller implementation, which follows the synthesis, will take place on a computer system. Before the A/D- and after the D/A-conversion an anti-alias-filter is placed in each channel. To incorporate their phase shifts, the identified plants $\underline{\underline{G}}_i$ will be extended by analytical models of the filter. The passband of the filter has the same characteristic than a Butterworth filter of 8. order with identical cut-off frequency. Thus a model of the filter can be easily obtained by using the MATLAB command `butter`. Comparative measurements confirm this approach. The last element that has to be added to the extended plant is an anti-spill-over filter, which is realized as an Butterworth low-pass of 4. order with a cut-off frequency at 55 Hz. It is placed at the input of the plant. At the implementation stage it will be placed behind the controller to prevent unwanted excitation of higher harmonics. The configuration of the extended plant $\underline{\underline{\tilde{G}}}_i$ for the synthesis of the controller shows figure 9. The controller design is carried out with the *μ-Analysis and Synthesis Toolbox* of MATLAB. The weighting scheme $\underline{\underline{\tilde{P}}}_i$ with the extended plant $\underline{\underline{\tilde{G}}}_i$ is a parameter of the function `hinfsyn`, which operates the iteration process to generate an H_∞-controller. The order of the controller arisen is reduced with the modal Hankel reduction afterwards. The process is repeated with constant weighting functions for each operating point. After reduction the average controller order is about 13.

4.4. Implementation and Results

Within the scope of the collaborative research center 562 it is planned to implement the two controls, structural and robot control, mentioned above on a PC with the realtime operating system QNX. A digital signal processor (DSP)-board is attached to each controller to do the A/D- and D/A-conversion. The two DSP-boards and the QNX-PC are connected via Firewire. During the test stage, whose end will be reached soon, the controller is

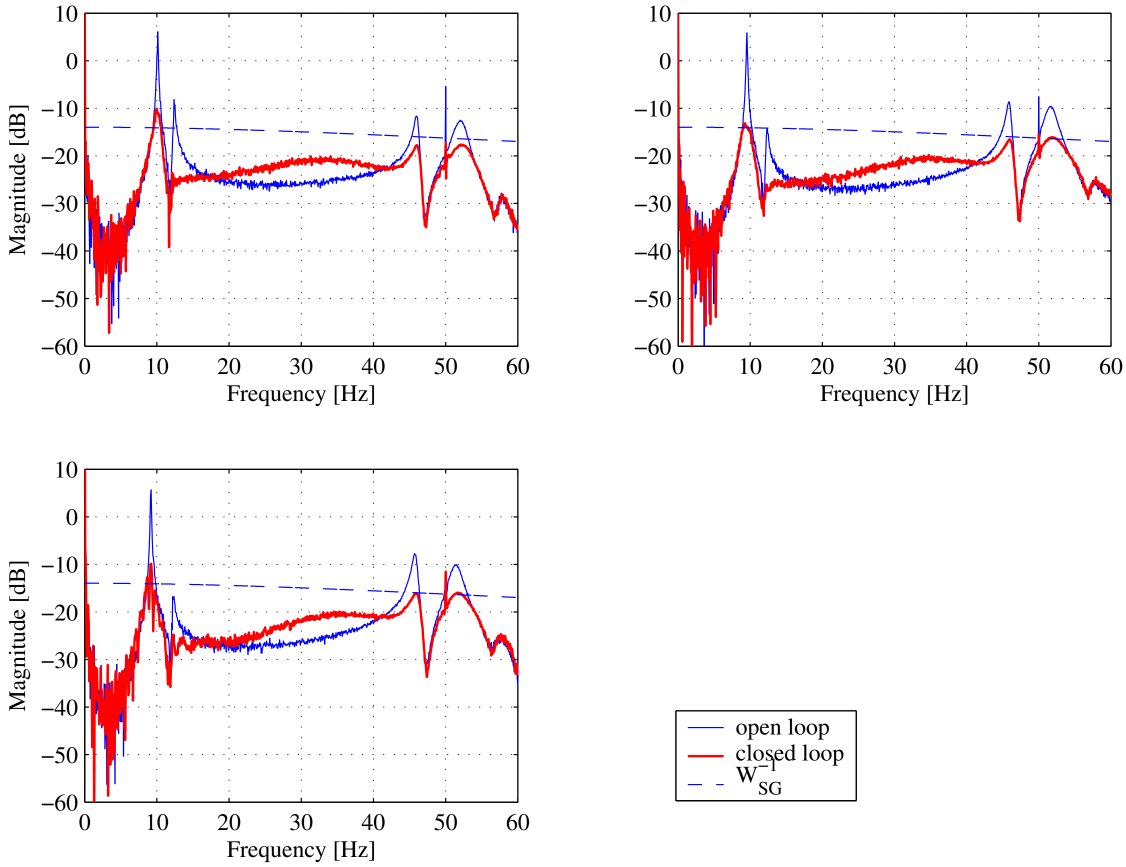

Figure 10. Open- and closed-loop FRF; top left: without additional mass, top right: additional mass 126 g, down left: additional mass 222 g

realized on a *dSpace* prototyping system. At the Hannover Fair 2004 the implementation on QNX should be completed.

The control cycle is 1 kHz and the anti-aliasing-filters from *Kemo* are set to a cut-off frequency of 500 Hz.

The performance and the function of the control system cannot be presented adequate in this article because of its complexity. Therefore only the results for operating point 1 are described. To compare open- and closed-loop behavior the Ono-Sokki FFT Analyzer is used to measure the frequency response function from actuator 1 ($w_{v,1}$) to the acceleration of the effector (y), see figure 7. In the closed-loop system the test signal of the Ono-Sokki and the control variable are overlaid. To get an overview over the systems performance these measurements are done with and without additional masses. The results are resumed in figure 10.

It can be seen, that in the case of an additional mass of 126 g, for which the controller was designed, the performance specification, formulated through W_{SG}^{-1}, is fulfilled. The robustness of the controller in the two other load cases is related to a decreasing performance. This fact is clearly seen in the exceeding of the inverse weighting function by the FRF. The vibration suppression of the first mode is in the optimal case 19 dB and in the two remaining 16 dB.

5. CONCLUSION AND OUTLOOK

The demonstrator described in this article is assembled completely and ready for use in the current project stage. It is a functional example for a consequent realization of adaptronic in a parallel robot. The good experience in consideration of vibration suppression confirm previous plannings and affirm the assumption, that this concept could be realized successfully on other robot structures.

Future workings will be limited on the sector of controller synthesis. Further increase of vibration reduction in the four selected modes is a topic. Additionally the control will incorporate several higher harmonics. For the realization of these tasks the usage of new control algorithms like μ-Analysis and Synthesis will be extended.

REFERENCES

1. S. Algermissen and T. Weyer, *Modellbildung eines VW Bora Daches unter Verwendung experimentell ermittelter Modaldaten*, IB 131-2002/36, DLR e.V., 2002.
2. K. Zhou, J. C. Doyle and K. Glover, *Robust and optimal control*, Prentice-Hall, 1996.
3. G. J. Galas et al., *μ-Analysis and Synthesis Toolbox* , The Mathworks Inc., 2001,g
4. G. Ohira, *Active Control of Machine Tools*, Japanese Journal of Tribology 38 / 8, pp. 1037-1046, 1993.
5. J. Hesselbach and B. Helm, *Adaptronics in Machine Tools*, Production Engineering, Vol. VII/1, pp. 83-86, 2000.
6. F. Campanile, R. Lammering and J. Melcher, *High Precision Form Measurements through the use of adaptive structures Technology*, Third European Conference on Smart Structures Technology, Lyon, 1996.
7. S. Olsson, *Active Vibration Control of Cutting Operations*, Adaptronic Congress 2001.
8. S. Kock, *Parallelroboter mit Antriebsredundanz*, VDI Fortschritts-Berichte, Dsseldorf, 2001.
9. TU Braunschweig, DLR Braunschweig, *Robotersysteme für Handhabung und Montage - Hochdynamische Parallelstrukturen mit adaptronischen Komponenten*, Antrag Sonderforschungsbereich 562, 2000.
10. W. Kortüm and R. S. Sharp, *Multibody Computer Codes in Vehicle System Dynamics*, Volume 22 of Supplement to Vehicle System Dynamics. Swets & Zeitlinger, 1993.
11. W. Kortüm, D. Sachau and R. Schwertassek, *Analysis and Design of Flexible and Controlled Multibody Systems with SIMPACK*, Space Technology, Vol. 16, No. 5/6, pp. 355-364, 1996.
12. M. Rose and D. Sachau, *Multibody Simulation of Mechanism with Distributed Actuators on Lightweight Components*, SPIE's 8th Annual International Symposium on Smart Structures and Materials, Newport Beach CA, 2001.
13. M. Rose, R. Keimer, E. Breitbach and L.F. Campanile, *Parallel Robots with Adaptronic Components*, ICAST, 13th International Conference on Adaptive Structures and Technologies, Potsdam/Berlin, Germany, 7-9 October, 2002.
14. E. Breitbach, R. Keimer, M. Rose and D. Sachau, *An Adaptronic Solution to Increase Efficiency of High Speed Parallel Robots*, ICAST, 12th International Conference on Adaptive Structures and Technologies, College Park, Maryland, USA, 14-17 October, 2001.
15. R. Keimer et al., *Adaptronische Schwingungsunterdrückung an hochdynamischen Parallelrobotern für Handhabung und Montage*, Intelligente Leichtbau Systeme (ILS), Hannover, 9.-10. September, 2003.