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Active Vibration Suppression in Parallel Mechanisms for Handling and Assembly

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ABSTRACT

Parallel kinematics offer a high potential for increasing performance of machines for handling and assembly. Due to greater stiffness and reduced moving masses compared to typical serial kinematics, higher accelerations and thus lower cycle times can be achieved, which is an essential benchmark for high performance in handling and assembly. As high accelerations lead to vibrations of the mechanisms tool center point, thus increasing cycle times or decreasing precision, an active vibration suppression is incorporated to further enhance the performance of these parallel robots. This paper focuses on two aspects of vibration suppression in this class of machines, on the one hand the design process for the active members is discussed. Different kinds of piezo-actuators are taken into account and the rationale for choosing surface mounted piezo-patch actuators in combination with CFRP structural parts is given. On the other hand the specific complications of doing control for vibration suppression in parallel robots is presented. As solution a robust control scheme, taking into account the changing properties of the structural dynamics of parallel robots is characterized. Experimental data on the effect of vibration suppression on a 4-DOF parallel mechanism for handling and assembly is presented, demonstrating the validity of the presented concepts.

Keywords: Handling and assembly, parallel kinematics, vibration suppression, robust control, piezo actuator

1. INTRODUCTION

Three possible devices can be used to influence the structural dynamics of the robots und thus do vibration suppression

- drives of the robot,
- joints of the structure,
- bar members of the structure.

While especially the use of joints is discussed in [1,2], a focus of this paper is placed on using the bar members of the Robots, as they

- do not interfere with the positioning and control of the kinematics (which is mostly seen as addressing rigid body motion) in opposite with using the drives, where rigid-body control and vibration suppression act on the same actuator,

- are less complex than joints, which concentrate complex mechanical elements in a small amount of space (like axles, bearings),
- offer themselves as possibility to integrate further functions beside their load carrying function as vibration suppression.

From the bar members rods (i.e. members with nearly just longitudinal loads) are focussed here due to them being frequently used as components of parallel kinematics.
A robust gain-scheduling control is used as control scheme to take into account the changing structural dynamics of parallel kinematics in the working space.

2. ACTIVE RODS FOR VIBRATION SUPPRESSION IN PARALLEL ROBOTS

2-1. Choosing Actuators

From the vibration suppression point of view, the goal of the design process is to maximize actuation stroke in order to give optimal authority for control, as the actuators are not operating against a global stiffness in general. In consequence, high forces are not required, but high actuation strokes are essential to effectively reduce vibration. While there is no global stiffness, structural integrated actuators have to work against local stiffness of the structures building the robot components, because usually these components are not solely built out of actuators.
First we will look at members actuated as a rod, i.e. just with an elongation. The actuation stroke Δl of a bar member is given by

$$\Delta l = \Delta l_0 \left(\frac{c_A}{c_S + c_A} \right) = \Delta l_0 \left(\frac{1}{1+V} \right), \qquad (1)$$

where Δl_0 is the free stroke of the actuator, c_A its stiffness and c_S the stiffness of the structure. The ratio V is given by $V = c_S / c_A$. In order to reach high strokes two parameters can be adapted:

- The stiffness ratio V, e.g. by maximising cross-section of actuating material and thus reach a low V.
- The free stroke Δl_0, e.g. by maximising the length of the actuator, as Δl_0 is determined by the length of the actuator and the active strain of the actuating material.

Due to its good industrial availability and its well known behaviour, piezoceramic material is chosen as actuator. Different topologies of actuators are available. The piezostack type is better suited to address the minimizing of V due to high cross section area while patch-actuators are better suited to optimize Δl_0 as they can be applied along the whole length of a rod without adding an abundance of weight.

2-2. Structural Conformity

Maximisation of actuation stroke is not the sole target of the design process [5]. Structural conformity is a second important goal. Structural conformity is defined by three characteristics:

- Ability of the active member to carry the external loads, resulting from the tasks done.
- Conformance with the requirement of low moved masses in the robot.
- Ability of the chosen actuator to carry the internal loads. Since piezoceramic material is brittle, a pre-stressing of the actuator is important for proper operation, as vibration suppression results in alternating dynamic loads.

Observation of these rules of structural conformity leads to different topologies for active rods depending on the chosen actuator. The need for pre-stressing and low moved masses leads to a topology with external pre-stressing through the structure and an internal rod to carry the elongation of the actuator in case of a piezostack as is depicted in the top of Figure 1. Tests with rods of this kind are discussed in [6]. When using patch-type actuators the overall design is getting more simple. Due to embedding the ceramics in a fibre-composite, pre-stressing of the brittle actuator is inherent of the setup as shown in Figure 2. The topology for active rods using patch-actuators is reduced to applying patch actuators to a carrying structure resulting in setups as shown in bottom of Figure 1.

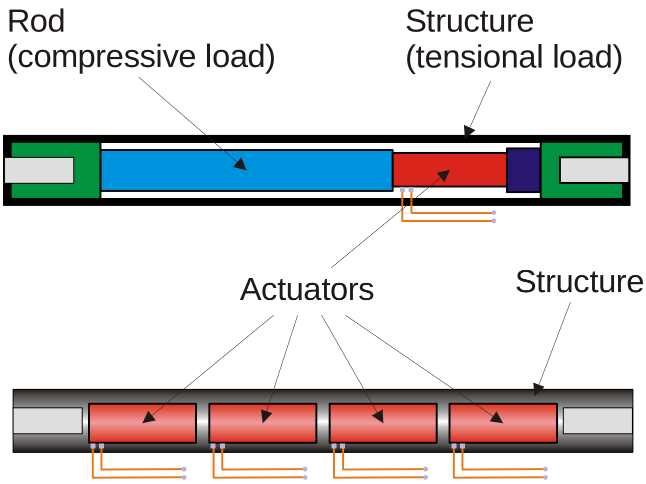

Figure 1. Different topologies of active rods

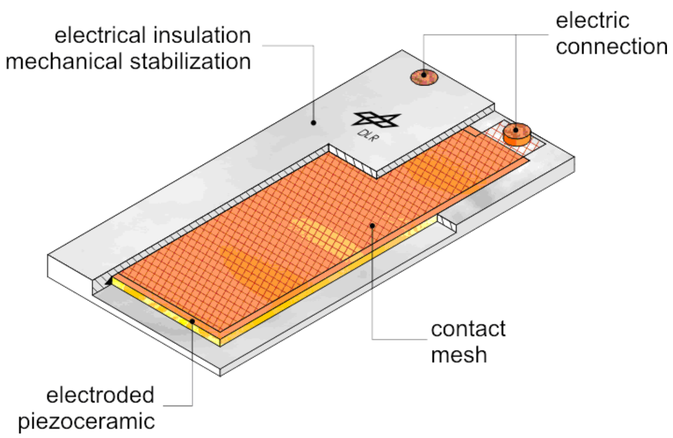

Figure 2. Piezopatch-actuator with inherent pre-stressing

2-3. Dimensioning of Rods with surface mounted actuators

The combination of patch-actuators with fibre reinforced plastics structures enables a flexible dimensioning of active members, since the fibre orientation can be used to adapt the stiffness of the structure according to the loads while still being able to optimize the stroke of the active member. To gain structural conformity on the one hand while getting optimal stroke on the other hand is easiest in this setup.

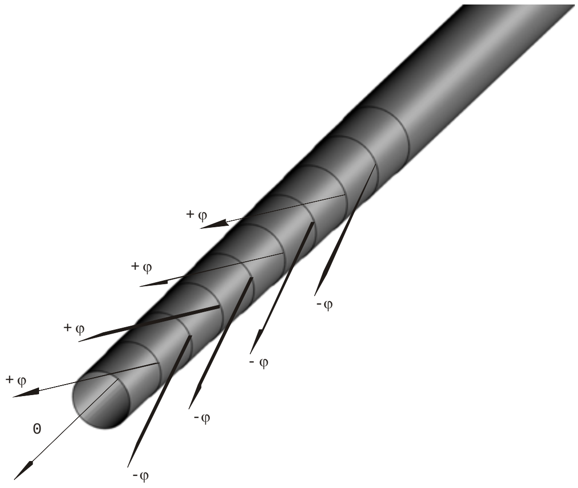

Figure 3. CFRP fibre-setup of rod

As example, Figure 3 depicts the fibre layout of a rod with a length of 42.4 cm, a radius of 1 cm and wall-thickness of 2 mm. The rod is used to demonstrate the dimensioning procedure [5]. The ratio *V* depends on the thickness of the used actuators and the angle of the fibre-orientation φ, as is depicted in Figure 4. An optimum is reached for high angles of fibre-orientation combined with high thicknesses of piezoactuators, respectively. Two failure modes exist for a given dynamic load (2500 N in this example) against which the rods have to be dimensioned. On the one hand a tensional load leads to a critical strain of the embedded actuators which has to be avoided. A shaded plain in Figure 5 shows the dimensioning load, parameters have to be chosen so as to need forces higher than this load to reach the critical strain. On the other hand compressional loads have to be below the buckling load of the rod. This leads to limitations regarding the ratio *V* due to these loads, because the parameters have to be chosen in a way that bearable forces are above the dimensioning load. This is illustrated in Figure 6 where parameters above the shaded plain comply with this requirement. Of course matters of manufacturability can further reduce the field of possible parameters. For example, the ability to apply thick ceramics to a circular rod of small radius is limited due to reaching the critical strain of the embedded actuators while bonding. The consideration of these constraints leads to dimensions shown by the dot in Figure 6, finally resulting in a rod with optimized stroke and structural conformity.

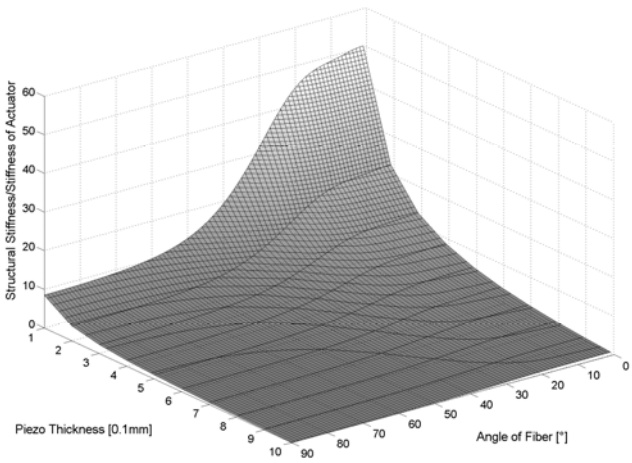

Figure 4. Ratio *V* between structural stiffness c_S and actuator stiffness c_A. More actuation authority for lowest ratio *V*

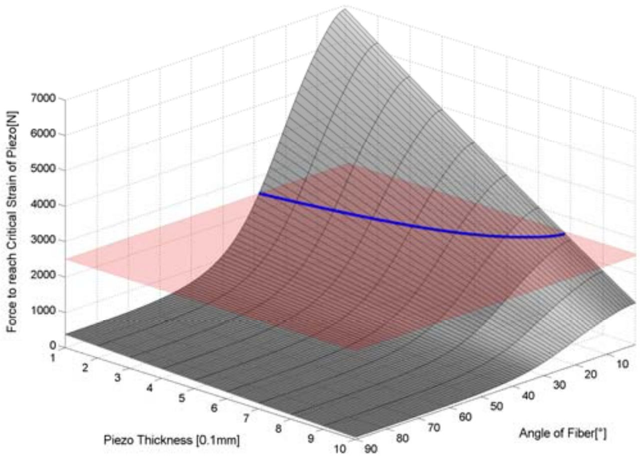

Figure 5. Force needed to reach the critical strain of the embedded piezoactuator. The shaded plane is showing the dimensioning load.

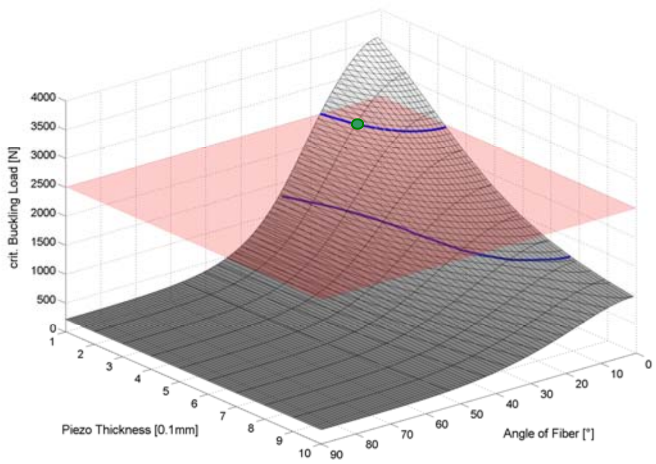

Figure 6. Buckling load of the rod. The shaded plane is showing the dimensioning load. Lower line showing limit from the critical strain (**Figure 5**). Dot showing the used configuration.

3. REALIZATION OF VIBRATION SUPPRESSION IN 4-DOF STRUCTURE *TRIGLIDE*

3-1. 4-DOF Structure *Triglide*

Systems with four degrees of freedom are often used in tasks for handling and assembly. To demonstrate the performance of parallel mechanisms in handling and assembly a 4 DOF structure *Triglide* is presented, where active rods as discussed in the previous chapter are implemented and tested (see Figure 7).

The *Triglide* mechanism is comprised of a 3-DOF parallel kinematic based on 3 parallell linear drives, providing 3 translational DOF, combined with a serially added rotational degree of freedom at the tool-center-point (TCP) as depicted in Figure 8. To give an impression of the physical dimensions the distance between the lower linear drives is 828 mm, while vertical distance to the upper drive is 450 mm. Besides being able to carry payloads up to 4 kg at 10 g acceleration this robot exhibits a increased working space, which is discussed in [8].

Figure 7. Rods for *Triglide*. Left side: single patch-actuator and rod, right side: complete link built of two rods

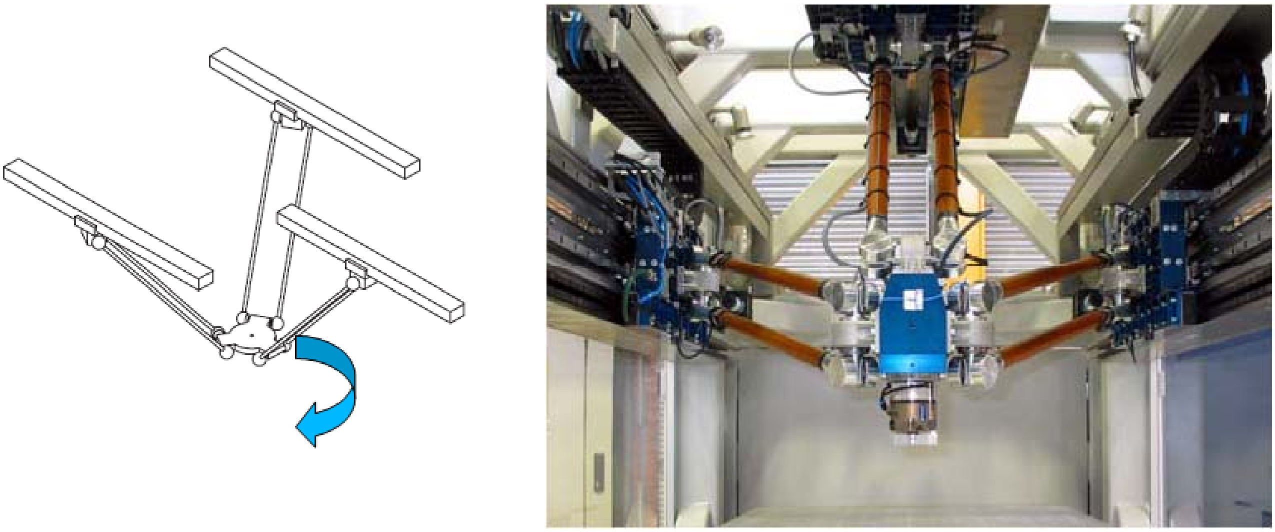

Figure 8. *Triglide* 4-DOF robot. Left side: kinematics, right side: actual robot with applied active rods

3-2. Robust Gain-Scheduled Control for Parallel Robots

3-2-1. Concept

Challenges of the implementation of vibration suppression in parallel robots are position-dependent vibration behaviour of the robot's structure and changing masses at the TCP. In contrast to changing masses, the position of the effector is known exactly during run-time of the robot, thus adapting of control to position-dependent changes is possible.

To cope with these changing parameters a Robust Gain-Scheduling control concept combined with a self-tuning approach was implemented and tested for the active structure of *Triglide* mounted on a passive aluminium frame without drives in a laboratory setup as shown in Figure 9. System identification and control synthesis were already tested in this setup [10]. The active structure was then mounted on the linear drives of *Triglide* robot (see Figure 10), replacing former passive structure.

The control architecture is a proprietary development of Collaborative Research Centre 562 and is based on real-time operating system QNX® 6.3 [11]. The main control thread runs at 1 kHz and smart-structure controller's Nyquist frequency is 125 Hz.

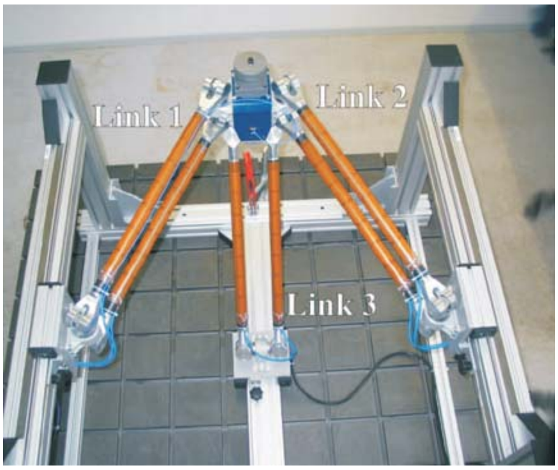

Figure 9. Triglide structure mounted in test-rig

For good control performance an accurate description of the plant must be available. As models from FE-calculations are especially deficient regarding phase response of the vibration, experimental system identification is used to derive the data needed for control synthesis. This system identification is automated and very fast; measurement takes 17 s and identification approx. 30 s [9]. Discrete state-space models with a specified number of states that describe the behaviour of the controlled plant very exactly are a result of this procedure.

A single non-linear model valid in the entire workspace is not preferred, keeping in mind that algorithms for synthesizing controllers are available and much easier and faster to use for linear models. In order to reach good performance the workspace is to be segmented. For the working space of *Triglide* changes of the vibration behaviour is assumed to only depend on the y-z position and is independent of the x position. This assumption is experimentally validated in [9]. The changing vibration behaviour is visualized in Figure 11 depicting the value of the first eigenfrequency of the structure measured in an evenly distributed mesh of the in y-z plane given by the dots in Figure 10. Based on these results, ten operating points where calculated to minimize gradient of eigenfrequencies between them resulting in segments defined by the rhombi in Figure 10 [13]. Identification in each point provides a controller valid for a corresponding region as given in Figure 12. In lighter coloured zones up to three of these controllers contribute to actuation, resulting in a smooth transition between the regions. Finally a comparison between the characteristics of the eigenfrequencies of the test-rig and direct-drive mounted robot show similar characteristics (see Figure 11), so that the derived workspace segmentation can be used in the real setup.

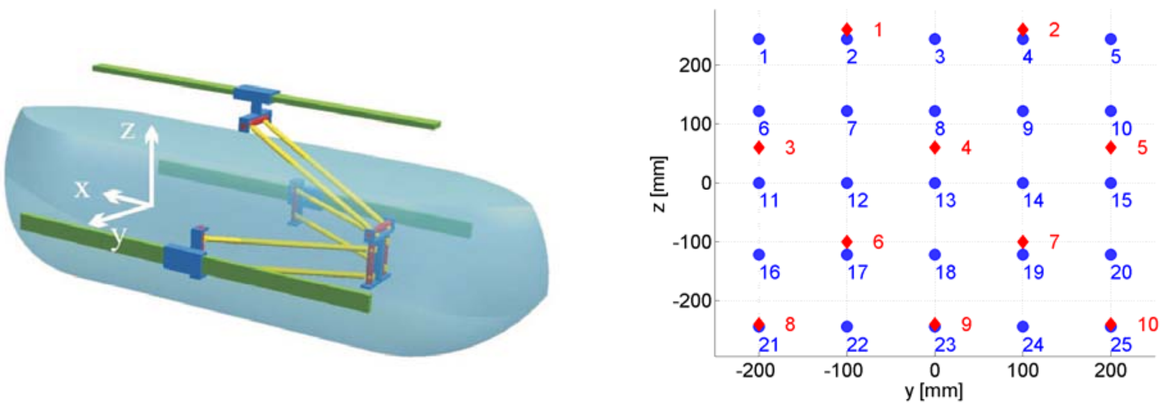

Figure 10. Positions in working space. Left side: Working space (shaded volume) with coordinate-system, right side: dots for positions to determine structural behaviour, rhombi for working points of single controllers.

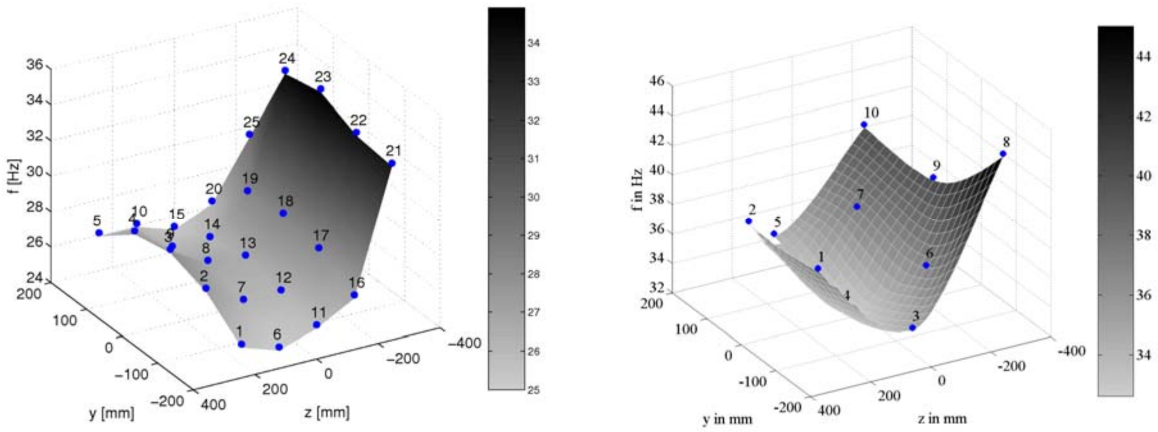

Figure 11. Characteristics of the first eigenfrequency of Triglide TCP. Left side: Characteristics while mounted in test-rig measured at the dots given in **Figure 10**, right side: Characteristics mounted on the drives.

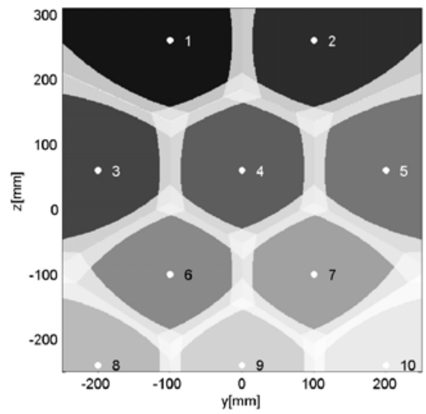

Figure 12. Segmentation of working space. Dots representing working point of single controller, light borders indicating positions where up to three single controller contribute to controller-output

3-2-2. Controller Design and Results

In robots with a large dynamic like *Triglide* the source of disturbances are inertial forces in consequence of acceleration and deceleration of the end-effector. These forces are modelled as disturbances $\underline{d}$ that enter the control loop (see Figure 13) in at the input of plant $\underline{\underline{G}}$. It is obvious, that the influence of the disturbances $\underline{d}$ on the controlled variable $\underline{y}$ is defined by $\underline{\underline{SG}}$ where

$$\underline{\underline{S}} = \left[\underline{\underline{E}} + \underline{\underline{G}}\,\underline{\underline{R}}\right]^{-1} \tag{2}$$

is the sensitivity of the control loop. Matrix $\underline{\underline{E}}$ is the identity matrix and $\underline{\underline{R}}$ is the controller. For limitation of control variable $\underline{u}$, the vector of piezo voltages, the maximum of the transfer function $\underline{\underline{RS}}$ from $\underline{r}$ to $\underline{u}$ has to be constraint. For the mathematical formulation of such constraints in the frequency domain the H_∞-norm is very suitable. The H_∞-norm of a transfer function matrix is defined as the largest singular value of the transfer matrix that occurs. The definition of design constraints is done with socalled weighting functions $\underline{\underline{W}}$. They are pre- and post-switched to control loop. With the controller pulled out of the loop, they form the weighting scheme for controller synthesis shown in Figure 13. Vectors $\underline{w}$ and $\underline{z}$ are called performance in and outputs. H_∞-controller is based on minimization of H_∞-norm [12]. In weighting scheme the controller $\underline{\underline{R}}$ tunes the H_∞-norm of transfer function $\underline{\underline{T}}_{zw}$ from $\underline{w}$ to $\underline{z}$ such that Controllers for all operating points are designed by automated

control synthesis [9].
As result Figure 14 shows the singular values for open- and closed-loop for the effector in operating point 1. Broadband reduction of vibration of up to 6.6 dB is realized. Narrow peaks less than 20 Hz and at 120 Hz source from motor control and electromagnetic disturbance. To demonstrate vibration control in time-domain, impulse responses of open- and closed-loop are calculated and displayed inFigure 15. Comparing the responses, control reduces decay time by approx. 70 ms. Therefore, absolute decay time can be reduced by factor 2.

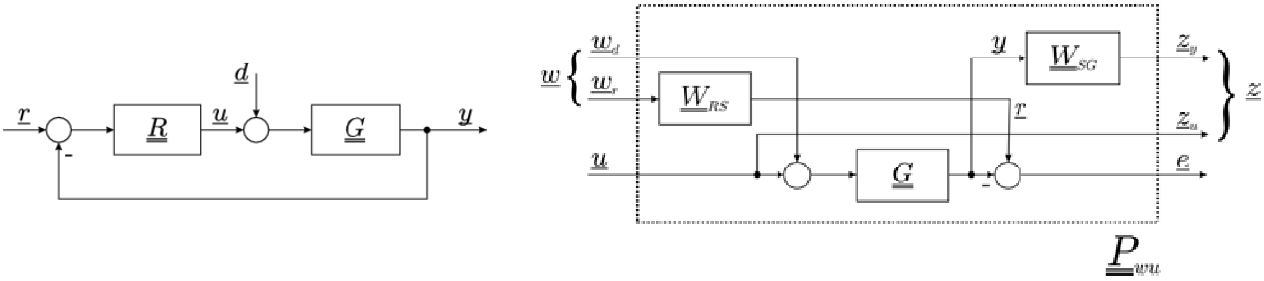

Figure 13. Control schematics. Left side:closed control loop, right side: weighting scheme

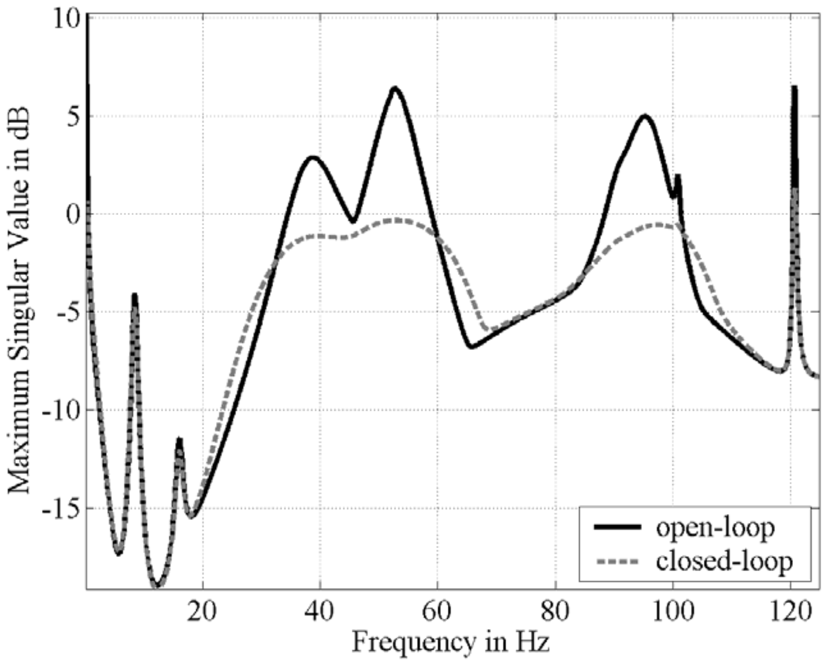

Figure 14. Maximum singular value of $\underline{G}$ (open-loop) and $\underline{\underline{SG}}$ (closed-loop) for operating point 1

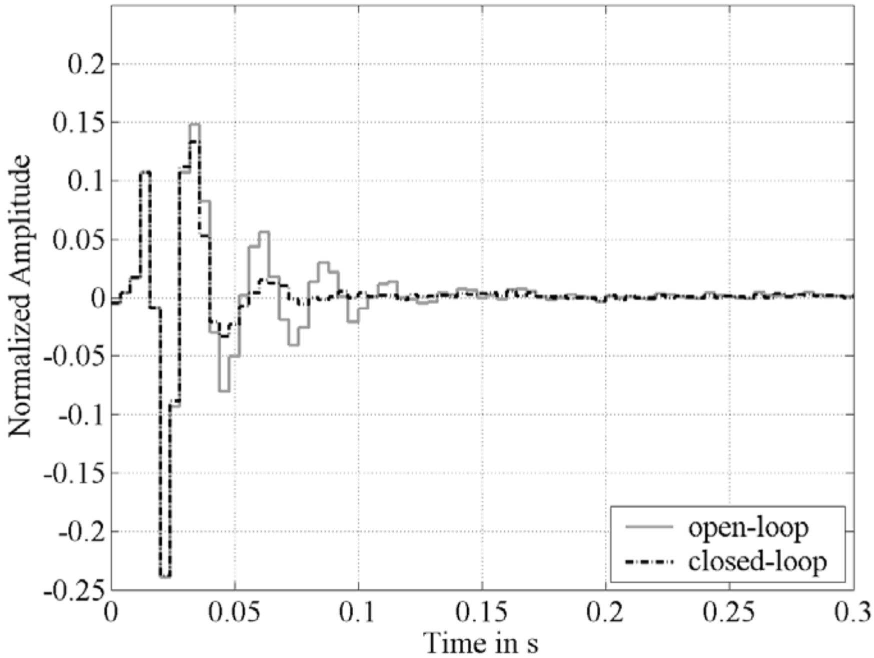

Figure 15. Impulse responses of $\underline{\underline{G}}$ and $\underline{\underline{SG}}$

4. CONCLUSIONS & OUTLOOK

Vibration suppression using piezoceramic actutators could be adapted to the problems of parallel kinematics using a suitable controller design. Surface bonded actuators as presented eased the design process, due to not needing external pre-stressing, especially adaption to different loads is eased.
The proposed Robust Gain-Scheduled controller-concept is suitable for vibration suppression in parallel kinematics with their changing vibration behaviour, as the shown first results demonstrate.
Regarding control the next steps will be the assessment of shortening of cycle-times using vibration suppression in realistic tasks of handling and assembly.
Regarding active robot members torsional and bending actuated robot members will be researched, in order to being able adress vibration-suppression in other classes of parallel robots.

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