Abstract
Vacuum is the absence of material and represents particle density lower than the atmospheric pressure. Ultra-high vacuum (UHV) is characterized by pressures lower than about 10^{-8} mbar. UHV conditions are important for scientific research. Surface analysis tools such as X-ray photoelectron spectroscopy and low energy ion scattering require UHV conditions for the transmission of ion or electric beams. In particle accelerators such as the Large Hadron Collider the beam pipes are kept at UHV for the same reason.[1] Hexapods can be used to precisely position a probe towards such a beam in particle accelerators. Hexapods are parallel kinematic actuators providing 6 degrees of freedom in a compact package.[2] Systems for high-vacuum environment are state of the art and systems for UHV with actuators outside[3] and inside the vacuum chamber are known. In a current research project a new powertrain for hexapod struts is developed to reduce the strut length for the usage in UHV environment. A well-known solution to reduce the length and therefore the overall height of a hexapod is to use a so called folded powertrain design. In such a design the motor shaft is parallel to the output shaft with an offset in between the axis. To transmit the torque in such a system a power transmission is needed. For UHV environment no mechanical solution to transmit a torque precisely between these axes was available. A new design based on a coupler mechanism was developed, produced and tested. In addition the couple mechanism can be used in low temperature environment. The test results will be presented and figures be discussed.

Hexapod, Parallel Kinematics, Powertrain, Hexapod-Strut, Ultra-High Vacuum, Precision

1. Introduction
A hexapod is a parallel robot consisting of a base plate, six linear actuators and an end effector – normally a top plate. The linear actuators, or struts of the hexapod, act as connections between the base plate and the end effector and have the ability to change their length. With this change in length, the end effector can be moved within six degrees of freedom. In figure 1 a typical design for a hexapod is shown and two different poses are illustrated.

![Figure 1. Hexapod in two different poses.](image)

The connection of every actuator with the base plate is the main difference between a parallel robot and a serial robot. With this parallelism of connections the stiffness of every actuator is added up, increasing the overall stiffness of the system. This rigid design is a key feature of hexapods in positioning applications.

One field, where hexapods for positioning applications are used, is for research and development. Vacuum environment is common within this field and therefore the hexapod mechanics needs to be vacuum compatible. This can have numerous reasons. In coating applications an atmosphere is needed which is free of contaminations. The same applies to applications where a beam of electrons or light is guided through space. In these applications hexapods e.g. manipulate probes, mirrors and therefore the beam vector or the beam source itself.

When designing a system for applications in vacuum environments, some restrictions have to be kept in mind. Used materials need to be vacuum compatible with low outgassing rates corresponding to application needs and have to withstand high changes in temperature, ranging from -30 °C to 120 °C. The high temperatures are reached while the system is baked in order to reach ultra-high levels of vacuum. Furthermore it has to be considered the avoidance of virtual leaks, while designing and developing a system for the usage in vacuum environment. These are gas volumina that are trapped, for example by a screw in a threaded hole without an outlet. Finally the positioning system needs to be compact and small due to limited space in a vacuum chamber.

2. Design
Designing a compact hexapod for a vacuum environment there are different possibilities. The most effective way to reduce needed space for the mechanics in the vacuum chamber is to use mechanical feedthroughs between a vacuum chamber and the air side. Here the active mechanical actuators...
are located on the air side, and only passive struts are located in the vacuum chamber.[3] This is the most effective way to keep most mechanics outside the vacuum chamber. Unfortunately a special vacuum chamber, adding the mechanics and feedthroughs, needs to be designed for every customer separately. Additionally flexibility in using a different hexapod or position of the hexapod gets lost. A different possibility is to build a compact motorized system which can be used in a vacuum environment. This system can be easily added to different chambers and only a feedthrough for electronic power and signals is needed.

A well-known solution to reduce the length and therefore the overall height of a hexapod is to use a so-called folded powertrain design used in e.g. PI’s H-825[4]. In such a design the motor shaft is parallel to the output shaft with an offset in between the axis. To transmit the torque in such a system a power transmission is needed. Figure 2 shows a folded powertrain compared to a serial powertrain. The orange element is the transmission between motor shaft and output shaft. For UHV environments no mechanical solution to transmit a torque precisely with zero backlash between these two axes was available.

![Figure 2. Comparison between serial and folded powertrains.](image)

### 2.1. Concept

The new drive concept has to be able to withstand vacuum environments without gassing into the vacuum and thus preventing the vacuum system from reaching its desired pressure. The main functionality is that it has to be able to transmit the torque from the motor shaft to the output shaft with a high angular accuracy.

A coupling gear in the form of a parallel crank drive, which can be seen in figure 3, is seen as suitable because it can be manufactured with materials suitable for vacuum applications and transmits a rotary motion with a high angular accuracy. This kind of transmission element can be found in e.g. locomotives where it is used to transmit the torque from one pair of wheels to another. The parallel crank drive consists of two conrods (1) with an offset of 90 degrees. This offset is needed to prevent the driven crank disc from changing its direction of rotation when the corresponding conrod reaches its top or bottom dead center.

![Figure 3. Principle sketch of a crank drive in a folded powertrain.](image)

### 2.2. First Prototype

To reduce development time and costs most of the parts of the first prototype were taken from standard hexapod struts. Therefore the first prototype is not vacuum compatible and was only tested in standard environment. Only the parts for the transmission element were changed and vacuum compatible materials were used. Figure 4 shows the first prototype with a partial cut to reveal the parallel crank drive. The right crank disks are mounted in the housing via ball bearings. The left crank disks are mounted on the motor shaft and the output shaft. The coaxial crank disks are connected by intermediate cranks. The length of these cranks provides the mentioned offset of 90 degrees between the crank disks.

![Figure 4. Sectional cut of the first prototype.](image)

### 2.3. Optimized Prototype

During testing and qualification of the prototype some optimization possibilities were identified. Every time one of the conrods reaches the top or bottom dead center deviations in position accuracy of the prototype are measured. First the insufficient bearing system of the right crank disks was suspected. But this suspicion was proven wrong. Instead peculiarities of the coupling drive are the reason for these deviations.

![Figure 5. Identification of the drive elements in the principle sketch and the real crank drive. Based on [5].](image)

When calculating the degree of freedom with the standard equation taken from [5] the resulting degree of freedom F is zero as shown below. b describes the number of possible movements. Since the parallel crank drive is a planar mechanism, the resulting number of possible movements is three - two translational movements and one rotatory movement. n describes the number of single links. As shown in figure 5 there are five single links. g describes the number of joints. The crank drive consists of six joints (12, 25, 23, 14, 45 and 34 in figure 4). f_i describes the degree of freedom of the single joints. Every joint is a rotary joint with a degree of freedom of one.

\[
F = f(b, n, g, f_i)
\]
\[ F = b \cdot (n - 1) - \sum_{i=1}^{g} (b - f_i) \]

\[ F = 3 \cdot (5 - 1) - 6 \cdot (3 - 1) = 0 \]

Therefore the crank drive would not be able to move. But practice shows that this kind of drives is in fact able to move. The reasons for this are so-called passive bonds. When extending the equation above with these passive bonds the resulting degree of freedom becomes one and therefore the crank drive is able to move as shown in the equation below.

\[ F = b \cdot (n - 1) - \sum_{i=1}^{g} (b - f_i) + \sum_{j=1}^{f} (s_j) \]

\[ F = 3 \cdot (5 - 1) - 6 \cdot (3 - 1) + 1 = 1 \]

The passive bond in this case is the condition that the length of certain element pairs – specifically element 1 and element 3 as well as element 1 and element 5 in figure 5 - of the crank drive have to be equal.

This is implemented to the prototype by creating the possibility of length adjustments of the relevant drive elements. Therefore the manufacturing tolerances of the drive elements can be kept at a moderate level, reducing the costs of manufacturing, while meeting the conditions of the passive bond.

### 3. Qualification

To qualify and compare the struts during different optimization iterations certain qualification parameters are determined. These parameters are backlash, repeatability, linearity and the minimum incremental motion (resolution).

The backlash indicates the position error when the active moving part of the prototype changes its direction of movement. The repeatability describes how accurate a certain point can be reached multiple times. The linearity is a measurement for the uniformity of the movements of the prototype. The minimum incremental motion describes the distance of the smallest step the prototype can perform.

Backlash, repeatability and linearity are determined by moving the prototype in small steps along a defined segment of its travel range and measuring the position error between commanded and real position at every step. This measured position error is then used to calculate the qualification parameters. Such a measurement sequence can be seen in figure 7.

The minimum incremental motion is determined by commanding steps of decreasing sizes. If the step motion meets certain criteria, the step size is accepted. The smallest accepted step size is called the minimum incremental motion.

#### 3.1. Measurement setup

Figure 6 shows the principle structure of the measurement setup for the qualification of the prototype and its optimizations.

The setup consists of a fixed and a movable part. The prototype is mounted between these two parts. The moving part of the setup is mounted with flexure joints. The main advantage of this kind of joints is the absence of play and almost no friction within the joints. A controller is connected to the prototype and the measurement system.

The controller reads the data from the measurement system and compares it with the commanded position of the prototype. The qualification parameters are then calculated with the difference between commanded and real position of the prototype.

#### 3.2. Measurement results

The measured and then calculated qualification parameters of the final prototype are listed in table 1. These results were reached using the final prototype with a vacuum compatible stepper motor and a PI controller.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backlash</td>
<td>2.934 µm</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.209 µm</td>
</tr>
<tr>
<td>Linearity</td>
<td>7.204 µm</td>
</tr>
<tr>
<td>Minimum incremental motion</td>
<td>3.000 µm</td>
</tr>
</tbody>
</table>

Table 1: Results of the qualification of the final prototype.

As seen in figure 7 there are still periodical deviations with a period length of 0.5 mm. Every peak in the curve corresponds to the top or bottom dead center of a conrod. This leads to the assumption that the passive bonds mentioned in chapter 2.3 are not completely fulfilled. The presumed reason for this is that the length adjustment of the drive elements is highly subjective. The length of the elements is adjusted by feeling and therefore the quality of the adjustment depends on the skill level of the person assembling the drive.

![Figure 6. The measurement setup.](image)

![Figure 7. Plotted corresponding measurement sequence of the results showed in table 1.](image)

### 5. Conclusion

In various optimization iterations a working prototype of a new drive concept for folded powertrains for hexapods has been developed. While analyzing the first prototype peculiarities of the coupling drive, so called passive bonds, were identified to be the cause of unsatisfactory qualification results. A solution to comply with these passive bonds was developed. Figure 8 summarizes the qualification results of the different optimization iterations.
Finally the backlash was reduced to 2.934 µm and the unidirectional repeatability value was reduced to 0.209 µm. Using direct metrology using an additional sensor for measuring the position on axis the position accuracy can be improved additionally. All tests were performed in a laboratory facility in a standard environment.

6. Outlook

For future tests a prototype strut will be manufactured with regards to the UHV manufacturing guidelines. This prototype will be tested and qualified within vacuum environments. The thermal behavior, position stability, position error, repeatability, backlash and minimum incremental motion will be qualified within different pressure rates (down to UHV). The outgassing rate will also be analyzed to validate the strut performance.

If this test in an UHV environment is successfully a complete hexapod system with new UHV struts will be manufactured, and the system performance will be qualified. A rendered image of such a hexapod system with new UHV struts is shown in figure 9.

Figure 9. Rendered image of a hexapod system with new UHV struts.

References
[3] Rudolf, C; Mock, C; Gloess, R: Hexapod Systems for UHV

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