OPTOMECHANICAL SPHERICAL MANIPULATOR WITH AN ADJUSTABLE CENTER OF ROTATION

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INTRODUCTION

Compound lens testing with a Fizeau interferometer requires a spherical motion to align the mechanical axis of the return optic with the transmitted laser beam (Figure 1). However, the location of the exit pupil differs between lens types, from somewhere inside the lens for entocentric lenses up to infinity for telecentric lenses. This therefore requires a corresponding adjustment of the remote center of rotation (RCR) of the alignment stage. Typical goniometer stages have a fixed RCR and require two additional translational stages for this alignment procedure, leading to an unintuitive and time-ineffective adjustment. In fact, for the desired motion only three degrees of freedom (DOFs) is needed, while conventional stages will require at least 4 DOF. To accommodate the alignment of different lens types, this paper presents a 3-DOF spherical manipulator, whose RCR can be adjusted from close to the end-effector up to a rotation about infinity i.e. pure translation.

Besides optical kinematic mounts, such a spherical mechanism with an adjustable RCR could be used in other disciplines. For example in keyhole surgery, peg-in-the-hole assembly, or non-contact scanning of spherical objects.

In this paper we present a kinematic optomechanical mount for testing of different lenses in a Fizeau interferometer. First the

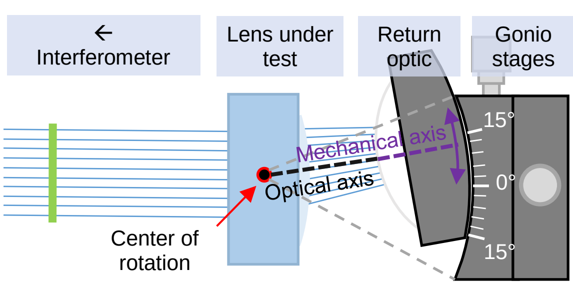


FIGURE 1. Fizeau interferometer lens testing requires a spherical motion of the return optic to align the mechanical and optical axes.

requirements, concepts and final design of the mechanism is presented, followed by an evaluation based on FEM and measurements of a 3D printed prototype.

DESIGN

Requirements

In Table 1. a list of requirements for the current application can be found. The main requirements concern the accuracy of rotation. The quality of lens testing will suffer when the RCR location differs too much from the optical center of the lens or if the motion is no longer pure spherical. Additionally, the stiffness of support should be sufficiently high to withstand the actuator forces and gravity and to prevent deflections in unwanted directions. Although the rotation round the mechanical axis (Figure 1) has no direct influence on the lens testing, it might result in unwanted parasitic motion in other directions and should be prevented as much as possible.

Conceptual design

We distinguish three main procedures to achieve such an adjustable spherical motion. In the first approach the motion is constrained by three rods whose axis intersect at the RCR. This leads to a spatial trapezoidal type mechanism whose base width is varied (parallel approach). The second type consist of stacking for two rotations about perpendicularly intersecting axes (serial approach). The third approach synchronizes the translation of a 2-DOF rotation and a 2-DOF

TABLE 1. List of requirements for the design.

Description	Value	Unit
Range of motion	± 3	°
Lateral motion	± 2	mm
Min. distance to RCR	45	mm
Max. distance to RCR	∞	~
Accuracy of spherical motion	5	μm
Accuracy of RCR location	15	%
Support stiffness (bending)	12	Nm/rad
Support stiffness (torsion)	0.2	Nm/rad

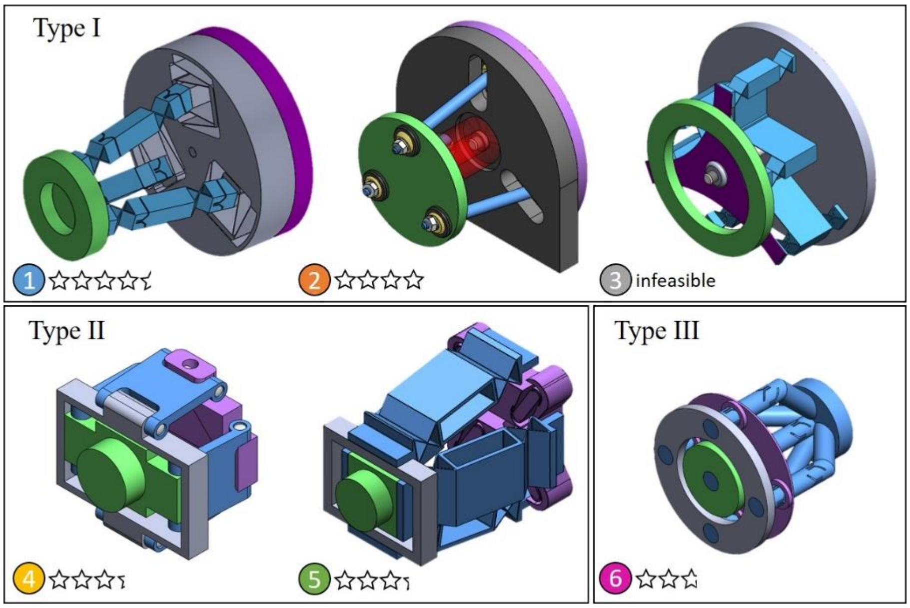


FIGURE 2. Six different concepts. With the end-effector (green), legs (blue), fixed world (grey) and the mechanism to change orientation of the legs (purple).

translation stage to obtain the desired 3-DOF motion (hybrid approach). In all these motion some form of synchronization between the different DOF is required.

Based on these three motion types, 6 designs were proposed (Figure 2), some based on conventional joint while other used flexure joints. Finally concept 1 was chosen because of simplicity and because the spherical motion is purely flexure mechanism based. Such flexure based mechanism are known for their high repeatability and low hysteresis making them ideally suited for high-precision motion applications [1].

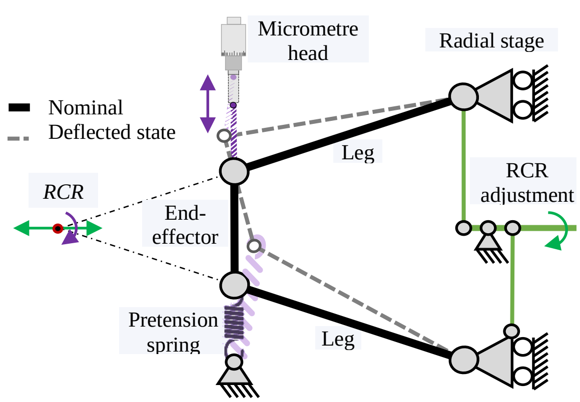


FIGURE 3. The working principle of the isosceles trapezoid mechanism with an adjustable remote center of rotation (RCR). By pulling the end-effector towards the micrometer head, the end-effector is deflected about the RCR. Varying the base width results in a changing RCR location.

Figure 3 shows the working principle of the chosen concept. The legs act as two force members such that the overall motion is constrained to the common intersection point of these legs. By adjusting the width of the base this intersection point changes, leading to a different RCR.

Detailed design

In Figure 4, the 3D printed functional model is shown. Each leg consist of two newly designed 2-DOF flexure joints. The base attachment point of the legs are placed on parallel flexure stage to allow for a changing base width. By changing the base width the RCR shifts from near the end-effector to infinity if the legs are parallel. To synchronize the individual legs a spiral slotted disc is attached at the back. The spherical motion itself is actuated by a micrometer (Figure 3). In this section some of these design elements are highlighted whereas the following section is devoted to the novel high stiffness legs.

As Figure 3 shows, the RCR is located at the intersection of the three legs of the mechanism. In order to shift the RCR closer or further away from the end-effector, the joints at the base are radially shifted in or outward from $22\,\mathrm{mm}$ to $33\,\mathrm{mm}$. The range of motion of the joints becomes $\pm 11°$. Together with the desired travel of the end-effector of $\pm 2\,\mathrm{mm}$, the joints in the legs must be able to tilt $\pm 15°$ in the main direction (R_y). Perpendicular to this tilting motion the joints in the legs should be able to rotate $\pm 2.5°$ in (R_x) direction, to allow for spherical movement.

As shown in Figure 4, three radial stages are present in the base to allow the radial movement of the legs. To prevent parasitic motion and save space, a compound parallel guide is used. By using two sets of antagonistic parallel leaf springs, connected at an intermediate body, the parasitic motion of the first set is compensated by the second. In addition, space is saved by slightly angling the parallel leaf springs.

These radial stages are actuated by a 'pin-in-slot' mechanism located at the backside of the base. This disk with spiral shaped slots rotates concentric with the z-axis using a shoulder bolt. The 'pins' are attached to the radial stages and protrude through the spiralling slots. To eliminate backlash in these slots, countersunk screws are used in combination with chamfered edges of the spirals. In order to keep the faces in contact, the disk is pre-tensioned by a spring over the shoulder bolt. This also results in helpful self-locking after adjustment of the RCR distance.

Large range of motion flexure joints

A new type of compliant cardan flexure is developed to function as the legs of the mechanism. The compliances in the legs are concentrated into two flexure hinges with intersecting centers of rotation, as shown in Figure 5. Since the support stiffness benefits from a lumped instead of distributed compliance [2] a small leaf spring hinge (SLSH) and cartwheel hinge (CH) are combined. The CH is responsible for the large deflection in R_y-direction of $\pm 15°$, while the SLSH can cope with smaller rotation of $\pm 2.5°$ in R_x- direction. It is important that the rotation centres intersect, so that the location of the RCR of the spherical mechanism is the same

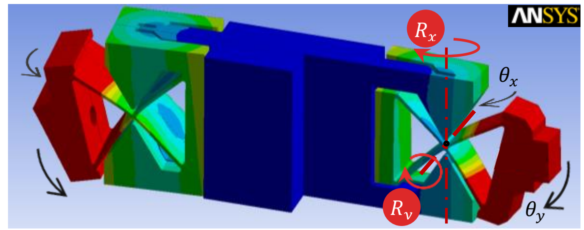


FIGURE 5. Simulated deformation plot of one of the legs in deflected state, with partial section view. This 3D printed part uses two novel flexure based cardan joints.

for tip and tilting motions. By integrating of the SLSH into the support of the CH a compact cardan joint design is obtained. Furthermore, the maximal allowable range of motion is physically limited by rigid parts of the joints in order to prevent the flexure from exceeding the yield stress.

To produce these flexures, 3D printing is the best suited production method due to the presence of some undercuts. Other techniques like wire-EDM cutting are feasible but require assembly from multiple parts. The geometry of the cardan joints in the legs is optimized using the mechanical properties of the PLA plastic, which is used in the functional model. The range of motion was optimized for the highest axial stiffness.

For analysing stiffness and range of motion two methods are used: The first method uses analytical approximations to predict the stiffness and maximal deflection of the joint using equations known from literature for the cartwheel and small leaf flexure joint [3]. These equations are used for calculating initial lengths. With a finite element model in ANSYS, a more detailed

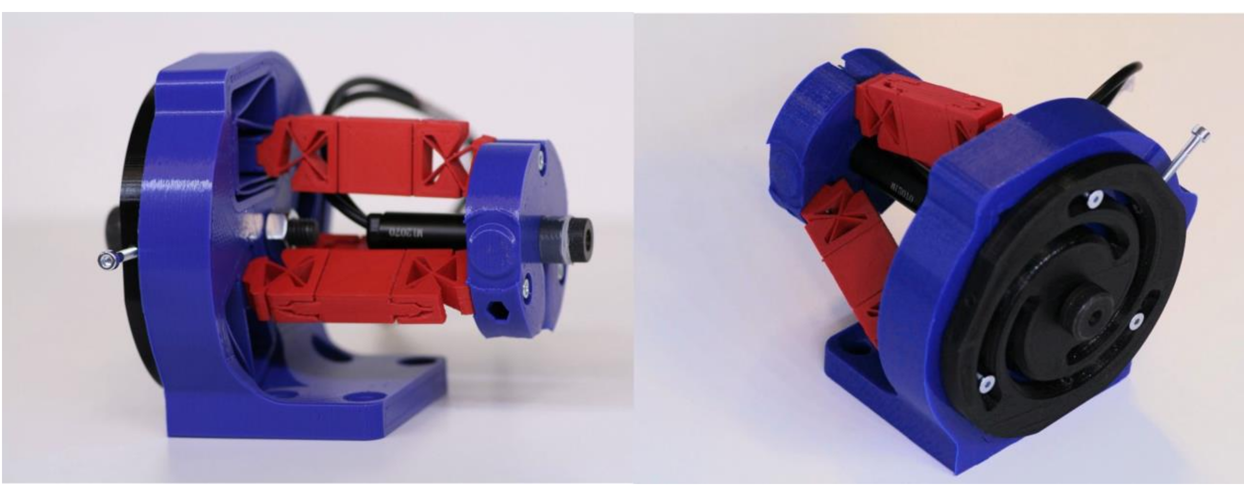
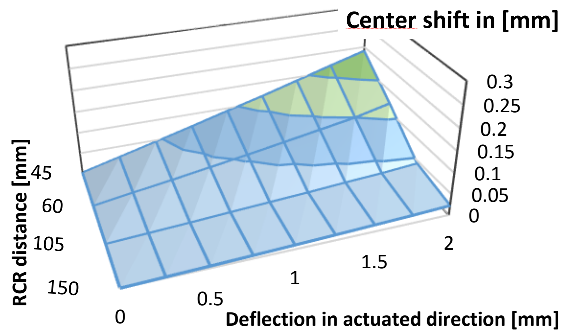


FIGURE 4. A 3D printed functional model of the spherical mechanism with adjustable remote center of rotation in the translating (left) and the pivoting (right) configurations. The legs are red, the spiral guide is black and the base and end-effector are blue.



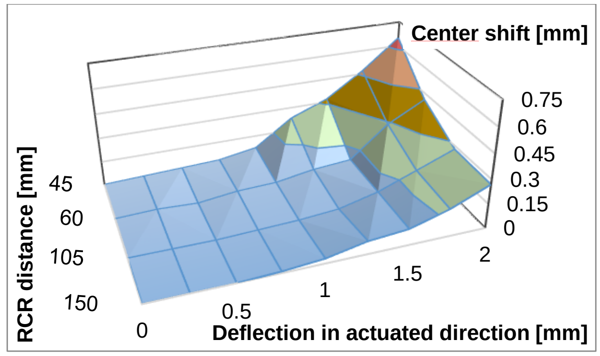


FIGURE 6. Left: Estimated lateral center shift of the RCR, using the PRBM model. Right: Experimentally determined lateral center shift of RCR of the functional 3d printed model.

design of the joint as a whole was optimized. It was found that the printed legs were able to reach the desired range of motion without failing. Other influences on maximal yield strength of the material are print temperature, layer height, infill percentage, porosity, and extrusion width [4].

EVALUATION

The mechanism is designed for spherical motion around a specified RCR. Ideally, the end-effector stays perfectly oriented towards this point for all motion. However, for this mechanism this is only true at in the initial position due to a kinematic change of the intersection point of the legs (Figure 3). This causes more rotation of the end-effector for a given translation, resulting in a different RCR. This phenomenon is called centre shift.

This centre shift was measured on the prototype by placing a camera sensor at location of the desired RCR. On the end-effector a laser pointer is mounted to illuminate the sensor at the RCR. In the ideal case, the camera sensor does not move during deflection. In practice, it does. Therefore, the change in spot location is taken as a measure for the centre shift. In Figure 6, the centre shift computed by a kinematic model and measurements on 3D printed prototype are shown.

As expected, the centre shift increases with larger deflections and a shorter distance towards the RCR. From the experimental validation, it could be determined that the centre shift increased more than expected for deflections larger than $1.0\ \mathrm{mm}$. This is attributed to the finite support stiffness of the mechanism. Since the actuation force is applied at the end-effector and not in-line with the centre of compliance, an additional angular error is introduced, causing a ‘diving’ motion of end-effector. The additional centre shift was found to be within the limits of the current application

CONCLUSION

In this paper we proposed a 3-DOF flexure based mechanism with an adjustable center of rotation to align a lens in a Fizeau interferometer. The mechanism consist of three flexure-based legs that connect to the end-effector in a trapezoidal manner. Each leg consists of two novel flexure-based joints that comprise of a cartwheel hinge and a short leaf spring hinge with intersecting axes. This compact design combines a relative high support stiffness with large range of motion in one direction. These legs are placed on synchronized parallel flexure guides to accommodate the radial movement of the base connection points for the RCR adjustment. The evaluation of a 3D printed prototype showed that the angular error of the end-effector is well below $0.1°$ for deflections smaller than $1.0\ \mathrm{mm}$. Although for larger deflections the angular error was increased up to $0.8°$ due to center shift, the desired accuracy of the Fizeau interferometer application has been demonstrated.

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