DESIGN OF POINTING MECHANISM FOR SATELLITE-BASED OPTICAL COMMUNICATION

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1. INTRODUCTION

The use of optical communication (OC) in ground applications using optical fiber is quite mature and common. The loss due to optic fiber media and polarization change [1] limits the use of ground-based OC. The satellite-based OC provides effective solutions to overcome these challenges of ground-based OC. One of the key requirements of satellite-based OC is high accuracy pointing. Small satellites with state-of-the-art technologies can achieve a pointing accuracy of 1.7 mrad with the best performance accuracy as low as 0.12 mrad [2]. Typically, large pointing motions of the OC system are done by the satellite, and for the fine motion, a high-accuracy parallel manipulator mechanism can be considered. The pointing errors due to joint clearance, friction, and unmodeled dynamics in a parallel manipulator can be eliminated to a large extent by replacing conventional joints with suitable flexible joints of the same rotation capability. Previous attempts at flexure hinge-based mechanisms have been limited to a workspace of a few degrees. In this study, we propose a flexure hinge-based high-accuracy pointing mechanism that can provide the same features as LaserCube (range ±10 degrees, accuracy <10 mrad) [3] with a lower number of actuators.

2. METHODOLOGY

A typical requirement of pointing in a satellite is ± 10 degrees about two axes. A three degree-of-freedom parallel manipulator is considered in this work. The mechanism is synthesized in three steps. First, the optimized configuration of the manipulator for the least passive joint rotation is chosen. Second, the suitable flexure hinge type is selected. Third, the chosen flexure hinges replace the passive joints, and dynamic simulation is carried out to analyze the suitability.

2.1. Kinematics of pointing mechanism

In a 3-RPS parallel manipulator, a top-moving platform is connected to a fixed base with three actuated legs. Each leg consists of a revolute (R) joint, followed by an actuated prismatic (P) joint, and, finally, the leg is connected to the moving platform by a spherical (S) joint. The configuration of the 3-RPS manipulator is shown in Figure 1 with *Ai*, *Bi*, denoting the R and S joints, and *Li* (i =1,2,3) denoting the motion at the P joints, respectively. A 3-RPS manipulator has three degrees of freedom – the principal motions are translation along the *Z* axis and rotation about the *X* and *Y* axes. The actuated legs are separated by 120º from each other. The spherical joint can be further simplified into three mutually perpendicular revolute joints intersecting at a point [4]. The Denavit -Hartenberg (D-H) table for each leg is given below, where the equivalent movement of a spherical joint can be modeled as Euler rotations, *Z-Y-X* or (321) while moving from the leg to the top (moving) platform. The quantity *a* is the radius of the triangular circumscribed top platform, and *b* is the radius of the triangular circumscribed base.

Table 1: DH table for a RPS leg

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	$\pi/2$	b	0	0
2	0	0	0	$\pi/2 - \theta_j$
3	$-\pi/2$	L_j	0	0
4	0	0	0	$(\theta_{S1})_j$
5	$-\pi/2$	0	0	$(\theta_{S2})_j + \pi/2$
6	$-\pi/2$	0	0	$(\theta_{S3})_j + \pi/2$
7	$-\pi/2$	0	0	$-\pi/2$
($j \in 1..3$), j=leg number, Lj = leg length ,				

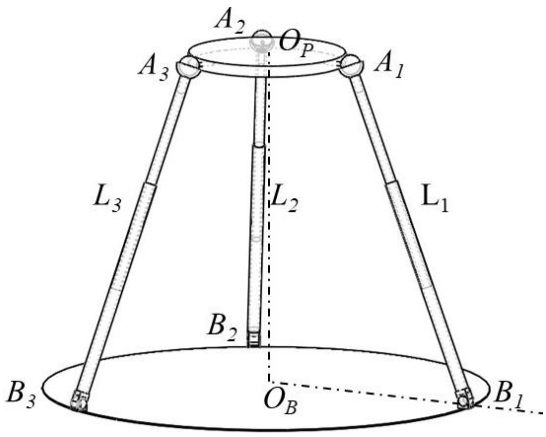

Figure-1: Schematic of a 3-RPS manipulator.

2.2. Optimization

Since the kinematic joints are planned to be replaced by flexural joints in a hardware, it is useful to minimize the rotation at the R and S joints. This is done by optimization in this work. The manipulator leg lengths (L_j), platform size (a), revolute joint rotation (θ_j), and spherical joint rotations (θ_{S1}, θ_{S2} and θ_{S3})$_j$ are considered for optimization. The manipulator is designed for a workspace of 20° (±10°), base radius b of 20cm, and height h of 31cm. The objective function is the L_2 norm and is given as

$$f(\theta) = \sum_{j=1}^{3} (\theta_{S1})_j^2 + (\theta_{S2})_j^2 + (\theta_{S3})_j^2 + \theta_j^2 \tag{1}$$

$$s.t \quad T(m,n) - T'(m,n) = 0, \qquad where\ m,n \in 1,2,\dots 4$$

where T and T' are the transformation matrix calculated moving via path $O_BB_1A_1O_P$ and O_BO_P. The optimization approach is a gradient-based (function *fmincon* in *Matlab*) and yields the values for the variables. For the desired workspace and constraints, the optimization for the 3-RPS gives the maximum values of the joint variables and the value of a as

[0, 7.29, 7.02, 71.3, 31.3, 0, -10.3, 2.6, 72.7, 34.2, 0, 2.9, -9.6, 71.8, 32.1, 10 cm]

To add further confidence to the obtained results, a genetic algorithm (GA) is used. GA uses past events to select future events and continuously improves the objective function. The objective function defined in Eq. (1) is minimized with a given set of initial points. The GA-based approach yields.

[0, 7.82, 7.02, 71.8, 31.4, 0, -10.8, 2.6, 73, 34.1, 0, 2.3, -9.6, 72, 32, 10.2cm]

and it can be seen that both approaches give reasonably close results.

The rotation angles observed at spherical joints are of the same order as that of top platform rotation, and the rotation angle observed at the revolute joint is a few degrees. Flexure hinges for such rotation can be designed monolithically with a deformable material. However, this will result in significant drift of the axis of rotation. The multibody leaf spring configuration [5] is a better choice for replacing spherical joints. A monolithic flexure hinge is selected for revolute joints as the rotation angles are in the order of a few degrees.

3. CONCLUSION

In this study, a 3-RPS parallel manipulator was chosen and designed as a pointing mechanism. The mechanism is designed for a rotational workspace of 20° (±10°). Two optimization techniques are used to determine the best solution for a symmetric 3-RPS mechanism, and they give similar results. The rotation observed at the spherical joint is almost the same as the rotation of the platform, and the least platform size results in lower joint rotation. These results will help in designing flexure hinges and the synthesis of manipulators for pointing mechanisms.

REFERENCES

[1] M. Peev, A. Poppe, O. Maurhart, T. Lorunser, T. Langer and C. Pacher, "The SECOQC Quantum Key Distribution Network in Vienna," 2009 35th European Conference on Optical Communication, Vienna, Austria, 2009, pp. 1-4

[2] NASA. State of the Art of Small Spacecraft Technology - Guidance, Navigation and Control. Dec. 2023. [Online]. Available: https://sst-soa. arc.nasa.gov/05-guidance-navigation-and-control

[3] Antonello, Riccardo et al. "High-Precision Dual-Stage Pointing Mechanism for Miniature Satellite Laser Communication Terminals." IEEE Transactions on Industrial Electronics 68 (2021): 776-785.

[4] A. Ghosal, Robotics: Fundamental Concepts and Analysis. Oxford University Press, 2009.

[5] Naves M, Aarts RGKM, Brouwer DM. Large-stroke flexure hinges Building-block-based spatial topology synthesis method for maximizing flexure performance over their entire range of motion. Mikroniek. 2017;57(3):5-9.