Laterally Unconstrained Magnetic Joint for Pointing, Scanning, and Steering Applications

Vlad Krylov* and Aaron Castillo*

Abstract

Laterally unconstrained magnetic joints enable a novel mechanism for tip-tilt and piston platform actuation. The mechanism is useful in applications where angular orientation of the platform in three-dimensional space needs to be controlled over a typical angular range of ±20 degrees. This mechanism comprises three linear actuators traveling along parallel axes and a platform supported by three joints at the ends of the actuators. The lack of a rigid lateral constraint within the magnetic joint enables the capability of platform to change orientation via the point contact interfaces. In this paper, the mechanical properties of the laterally unconstrained magnetic joint and their impact on tip-tilt platform performance are discussed.

Introduction

Tip-tilt actuation of a platform is a common task in many applications, especially flat mirror actuation in optical systems. Conventional mechanisms such as gimbal mounts, hexapods, and others are frequently pushed towards higher performance. Typical performance parameters include actuation range, speed, pointing accuracy, and cost.

The actuation speed of all mechanical systems is fundamentally limited by the moving mass of the payload and the actuation mechanism. A major advantage of the laterally unconstrained magnetic joint is the minimization of the parasitic moving mass required to actuate the platform. This in turn results in a higher actuation speed and lower cost. Increased reliability may be achieved through simplification and reduced component count.

Laterally Unconstrained Magnetic Joint

A practical implementation of the laterally unconstrained magnetic joint (the joint or the magnetic joint) consists of a permanent magnet having a flat surface interfacing and a ferromagnetic stainless-steel part having a spherical surface as shown in Fig. 1. The flat surface of the magnet may have nickel or other types of corrosion protective coatings, or a thin sheet of a bearing material, such as a sapphire disk. The bearing material creates a magnetic gap between the permanent magnet and the ferromagnetic metal.

The two interface surfaces within the magnetic joint have a point contact throughout the actuation range. The magnetic field produced by the interaction between the joint components results in an axial preload force and a lateral centering force. The axial force acts through the point of contact between the two surfaces perpendicular to the flat surface of the magnet. The lateral centering force is present when the two joint components are misaligned. Within the operating range, the lateral centering force magnitude increases with joint component misalignment.

The magnet and steel parts are both axially symmetric and have the same diameter. This configuration produces the fastest increase in the lateral centering force which is the desired property in tip-tilt platform attachment applications.

* Light Steering Technologies, Inc., Manchester, NH

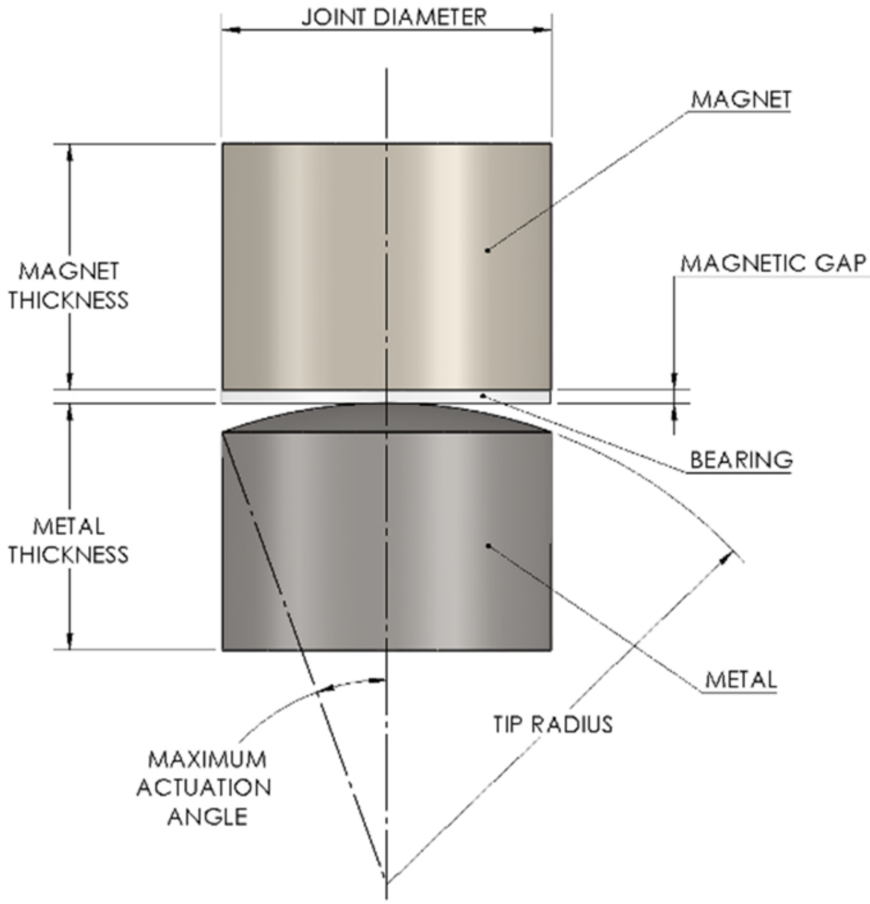

Figure 1. Basic Geometry of the Laterally Unconstrained Magnetic Joint

Other configurations of the magnetic joint, such as having both parts made from a permanent magnet or using another type of a convex surface, are possible; however, these are outside of the scope of this paper.

<u>Nomenclature</u>
Throughout this paper the following nomenclature may be used for brevity:

Joint: Laterally unconstrained magnetic joint

Magnet: The first component of the laterally unconstrained magnetic joint made from a permanent magnet material. In most applications it is a high grade of Neodymium Iron Boron magnet, which offers the highest force for expected operating temperature range.

Metal: The second component of the laterally unconstrained magnetic joint made from a ferromagnetic material. In most applications it is 416 or 430 stainless-steel, based on the trade between hardness and machinability. In environments where corrosion is not a concern other steel alloys may be used.

Bearing: A non-magnetic material rigidly attached to the magnet. In most cases it provides the magnet with corrosion protection and improve the joint bearing properties.

Tip Radius: Spherical radius of the second mating surface of the joint.

Piston-Tip-Tilt Platform Application of the Magnetic Joint

Efficient actuation of a tip-tilt platform is the most common application of the laterally unconstrained magnetic joint. The magnet component is attached to the platform side. The bearing surfaces of the three joints form a planar surface. In optical applications where the platform is a front surface mirror, the planar surface formed by the three joint bearings is parallel to the mirror. Such a configuration ensures that the lateral motion of the platform does not affect its pointing.

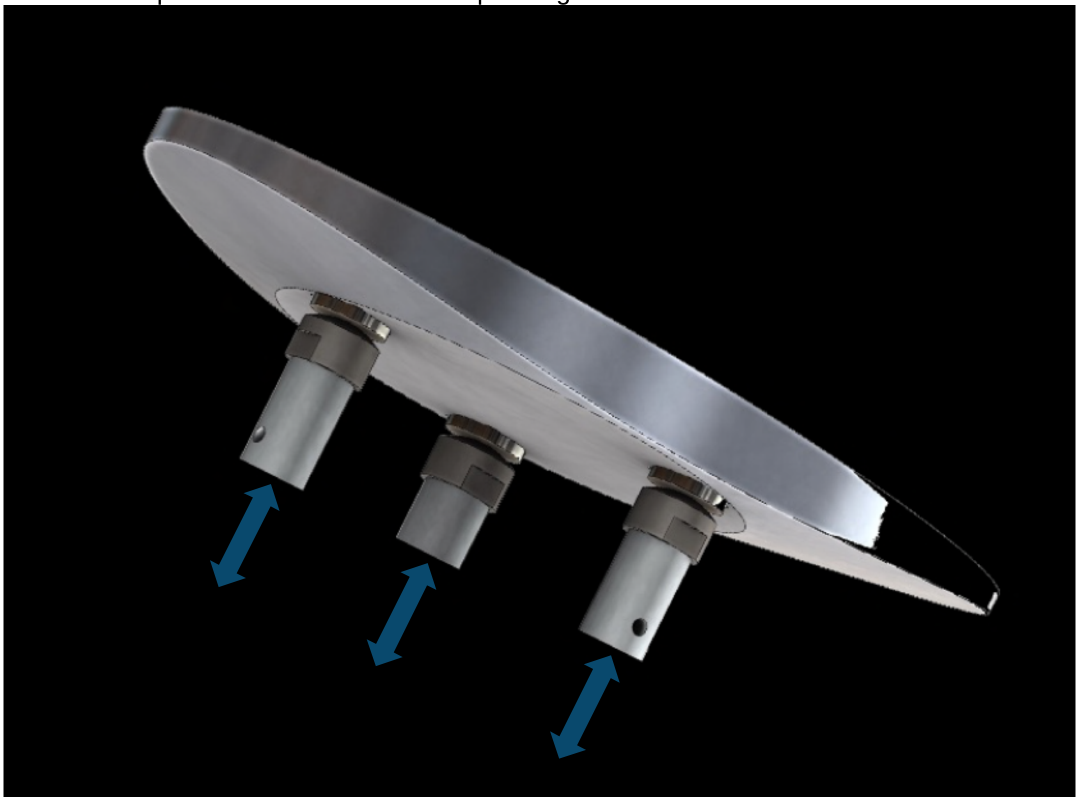

Figure 2. Tip-Tilt Platform Application of the Laterally Unconstrained Magnetic Joint

The mating joint component – metal tip – is attached to a linear actuator. The spherical radius of the metal tip and the bearing surface of the magnet interface through a point contact. This contact is preloaded by the magnetic force produced between the magnet and the metal tip.

The distance between the contact points of each actuator pair changes throughout actuation range, see Figure 3. The lack of rigid lateral constraint within the joint accommodates this change and allows the platform to float on the three metal tip points. The lateral magnetic force within the joint increases with de-centration of the magnet and metal tip thus maintaining the integrity of the system within the range of operating conditions.

The lack of rigid mechanical constraint in the platform mount has other potential benefits. In environments with large temperature variations, the platform can expand and contract independently from the base of the system to which actuators are attached. In optical applications this allows for a lighter mirror as the requirement for the structure rigidity is reduced. The modal frequencies of the system are also higher due to decoupling of the platform and actuators in all but one degree of freedom simplifying the control and improving the bandwidth in high frequency applications.

Figure 3. Tip-Tilt Platform Actuation Enabled by the Laterally Unconstrained Magnetic Joint

Joint Geometry

The parameters of the joint geometry such as diameter, thickness of each component, and the spherical radius of the tip are optimized based on application requirements. This optimization is focused on achieving the axial and lateral magnetic attraction forces that support the platform weight in the dynamic operation, actuation angle, environmental shock and vibration the system is required to withstand.

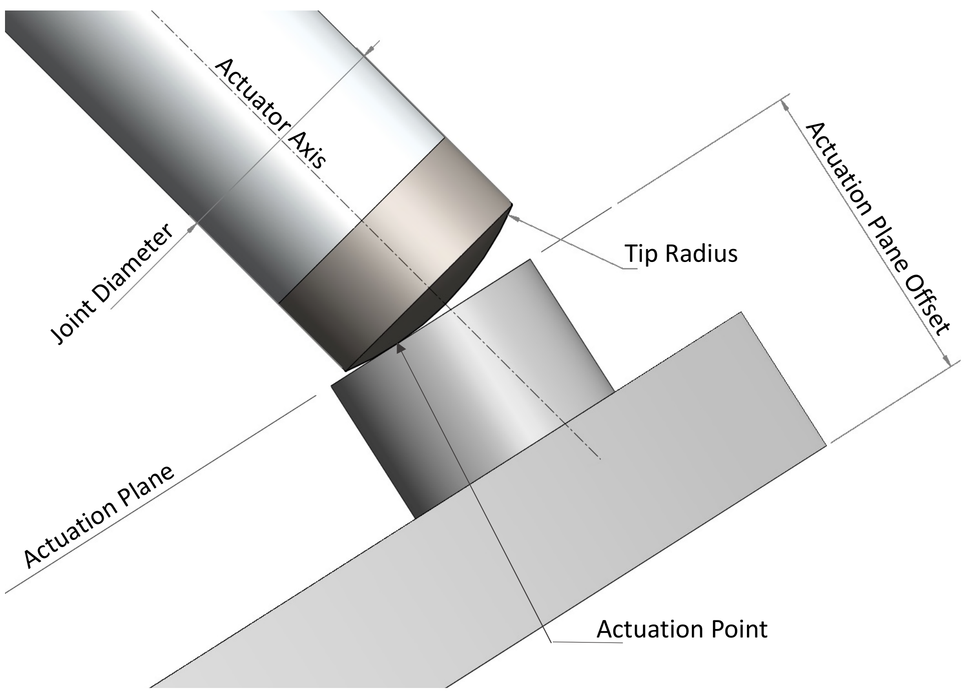

Figure 4. Impact of the Application Constraints on the Joint Geometry

The spherical radius of the metal tip is selected to accommodate the maximum actuation angle. Radii smaller than the maximum would compromise the joint attraction force in favor of lesser lateral displacement over the actuation range.

The minimum diameter of the joint is based on the actuation geometry and the maximum actuation angle. The joint diameter accommodates the travel of the point contact on the magnet bearing surface resulting from the change in the distance between the metal tips. The joint diameter is also a function of the required attraction force driving the size of the joint components. In practical applications we find the joint diameter being 2 – 3 times greater than the minimum for tip/tilt angle of 20 degrees.

Material Selection

Currently, the strongest known magnet type is Neodymium Iron Boron (NdFeB). There are multiple grades of NdFeB magnets, each with a specific B-H curve. The strongest commonly available grade is N52, which would be used in most implementations of the joint, except applications requiring an operating temperature above 80°C. In latter cases, magnet strength will be traded for higher demagnetization temperature. Fig. 5 shows a representative difference in the joint axial attraction force for two common NdFeB magnet grades for a specific joint geometry.

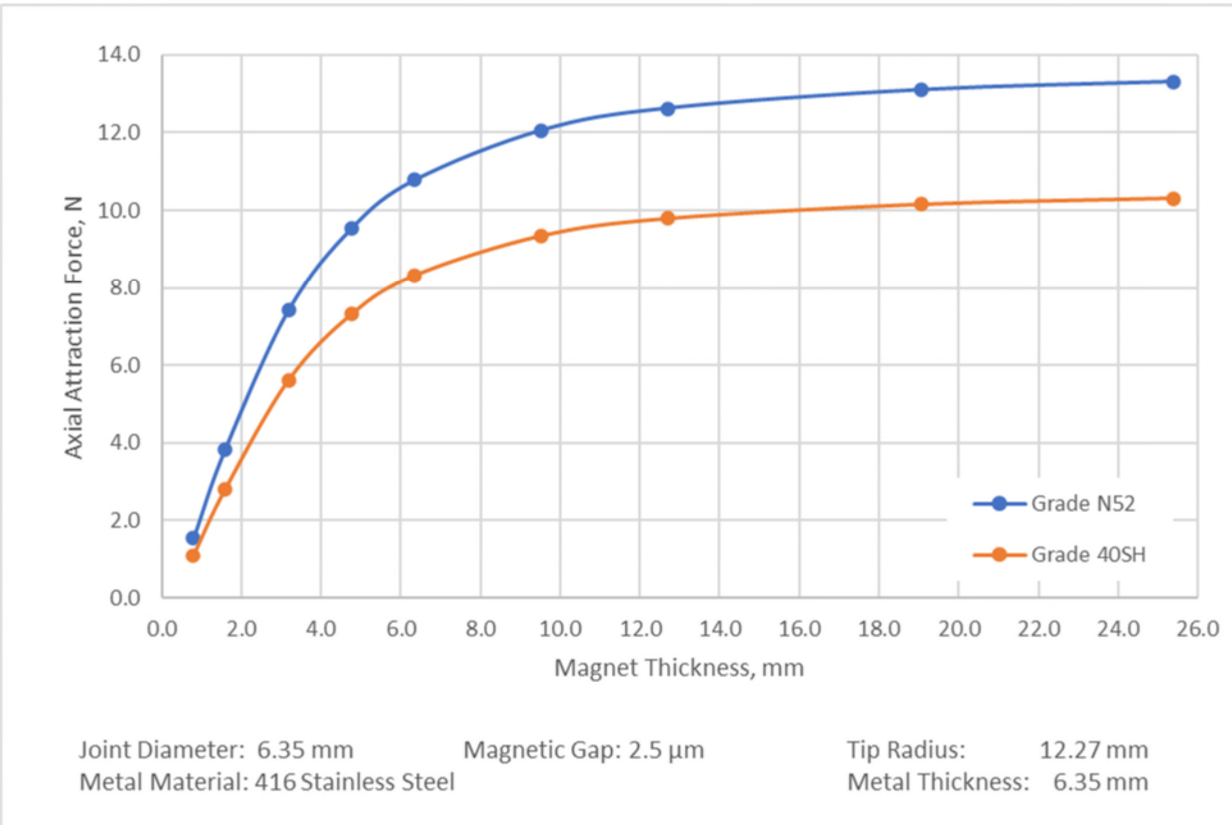

Figure 5. Axial Attraction Within the Joint for Common NdFeB Grades

Due to corrosion, in most expected application environments, ferromagnetic stainless steel would be the preferred material for the metal. There is no appreciable joint axial attraction force difference between common 400 Series ferromagnetic stainless steels, such as 416, 430, or 455.

Bearing material depends on the joint applications. For lighter platforms without demanding accuracy requirements, a polished nickel coating of the magnet ranging in thickness between 2.5 µm and 25 µm could be sufficient. When higher precision of motion is required, a 75 µm to 200 µm thick sapphire disk is bonded to the magnet.

Axial Attraction Force

Axial attraction force is the primary characteristic that defines the performance of the magnetic joint in an application. The optimization of the joint geometry is done based on achieving the axial attraction force required by the weight of the platform or other payload, dynamics of the application, and the environment.

This paper presents the results of simulation of axial attraction force for an aligned joint using commonly available sizes of cylindrical NdFeB magnets from 1.6 mm to 19 mm diameter.

To optimize the joint geometry, two derived parameters are considered:

- Joint attraction force per unit weight (N/g)
- Maximum axial acceleration (m/s^2) with a specific payload

Magnet thickness and metal thickness can be optimized for desired retention force based on joint diameter, tip radius, maximum deflection angle, magnetic gap, and materials. Fig. 6 shows an example of optimization for a 10 N attraction force.

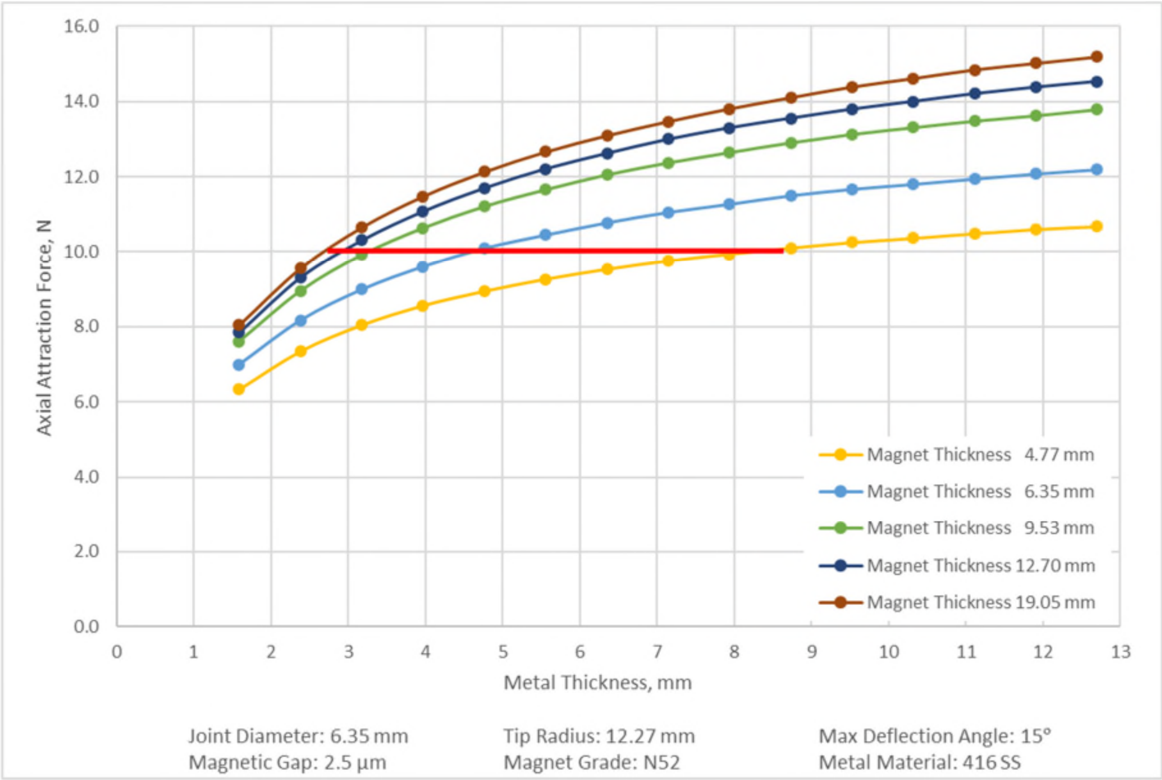

Figure 6. Axial Attraction Force as a Function of Component Thickness

From the attraction force plot alone, it is not clear which combination of magnet and metal thickness is the best choice. Fig. 7 shows the attraction force per unit weight for the same geometries. The red line represents the 10-N force selection. The attraction force per unit weight plot, when analyzed together with the attraction force plot, shows the preferred combination of the joint component thicknesses which offer the lowest joint weight and thus the best dynamic performance.

The maximum axial acceleration with the selected payload determines the acceleration at which the axial attraction force of the joint can no longer overcome the separating force of the mass consisting of the magnet, bearing, and payload. Fig. 8 shows the maximum axial acceleration for the same set of geometries and a payload mass of 75 grams. Red triangles show the 10-N force points.

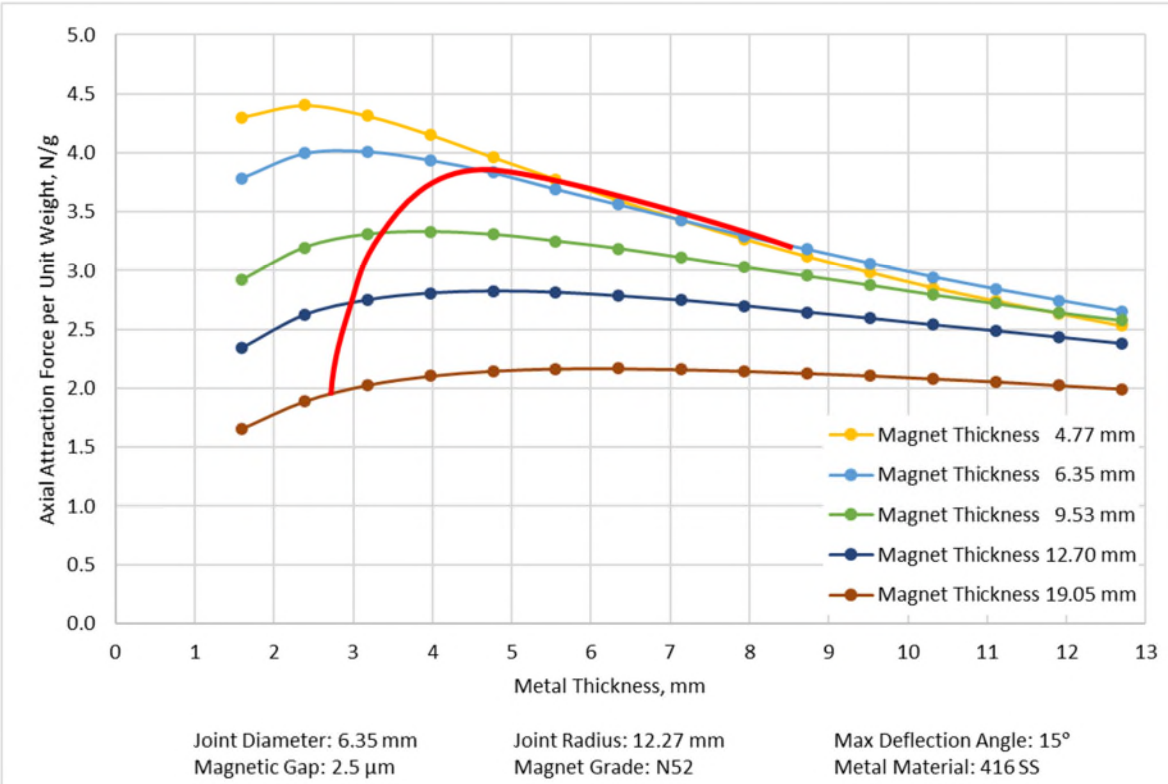

Figure 7. Axial Attraction Force per Unit Weight as a Function of Component Thickness

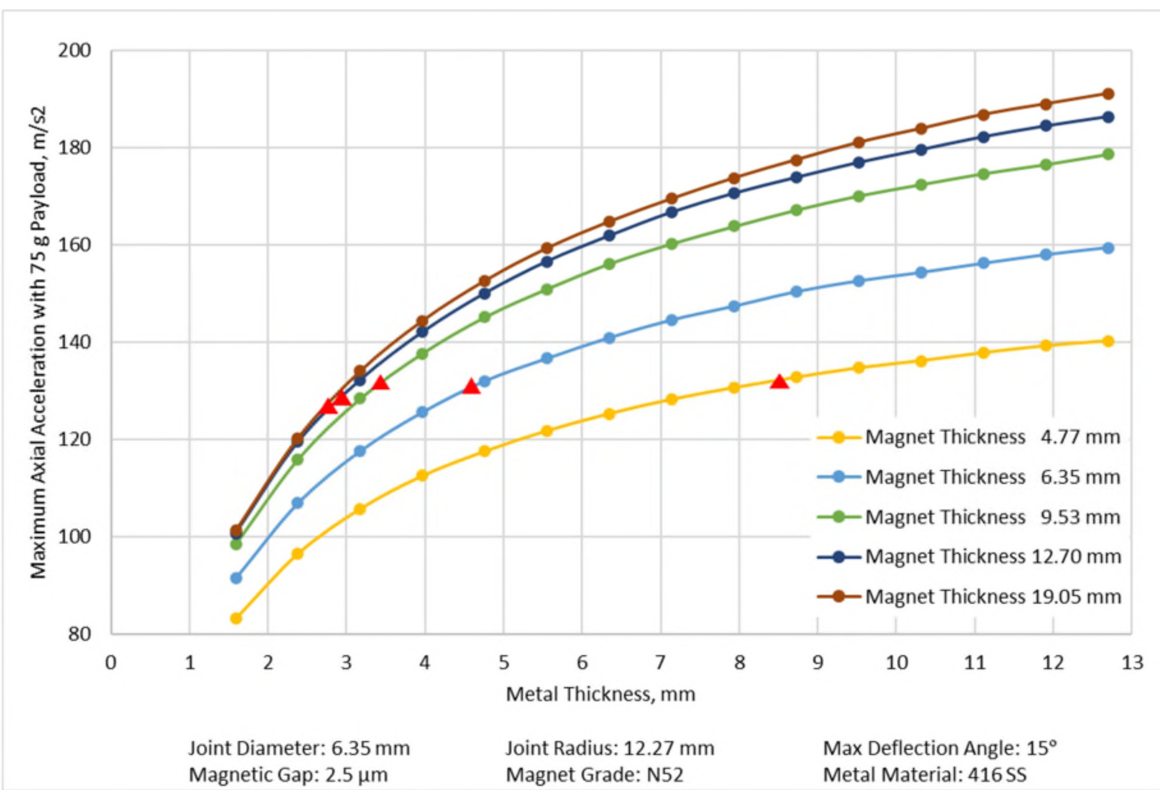

Figure 8. Maximum Axial Acceleration as a Function of Component Thickness

While the axial acceleration plot shows that the joint having magnet thickness of 9.53 mm and a metal thickness of ~3.3 mm slightly outperforms the joint having magnet thickness of 6.35 mm and a metal thickness of ~ 4.6 mm, this comes at a cost of greater weight, and actuator capabilities would need to be considered as part of the geometry selection. If actuator performance is one of the limiting factors, the latter joint geometry may offer the better overall system performance.

The air gap between the joint components depends on the tip radius. Smaller tip radii increases the air gap and thus lowers axial attraction force. In most joint applications, the radius is optimized to achieve the desired actuation angle, however, in some applications it may be beneficial to reduce the joint radius which would also minimize lateral displacement of the joint contact point over the actuation range.

Fig. 9 shows a typical dependence of the axial attraction on the tip radius. Data labels show the corresponding maximum actuation angle of the joint. In advanced joint applications, the gap between the joint components can be filled with ferrofluid to increase the axial attraction force at larger metal tip radii.

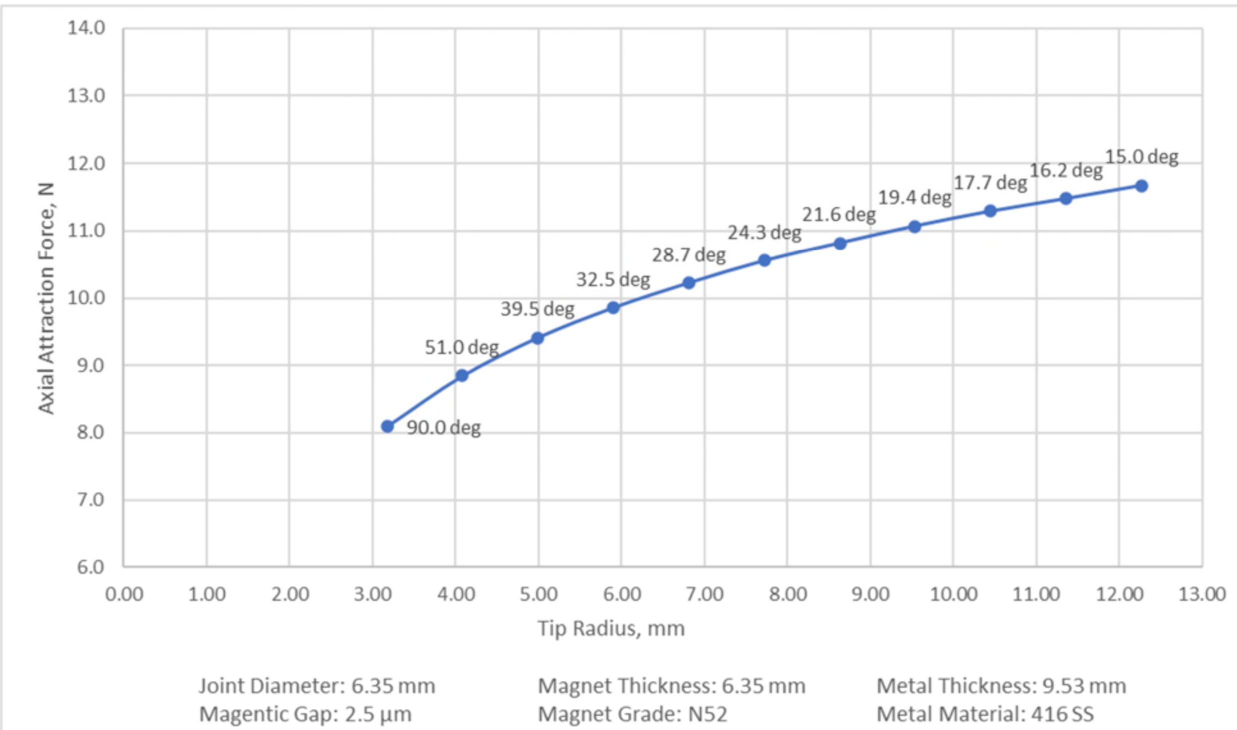

Figure 9. Axial Attraction Force as a Function of Metal Tip Radius

The attraction force within the joint reduces as magnetic gap increases. Typical implementation of the joint minimizes the thickness of the bearing material. An example of this dependence between magnetic gap and attraction force is shown in Fig. 10.

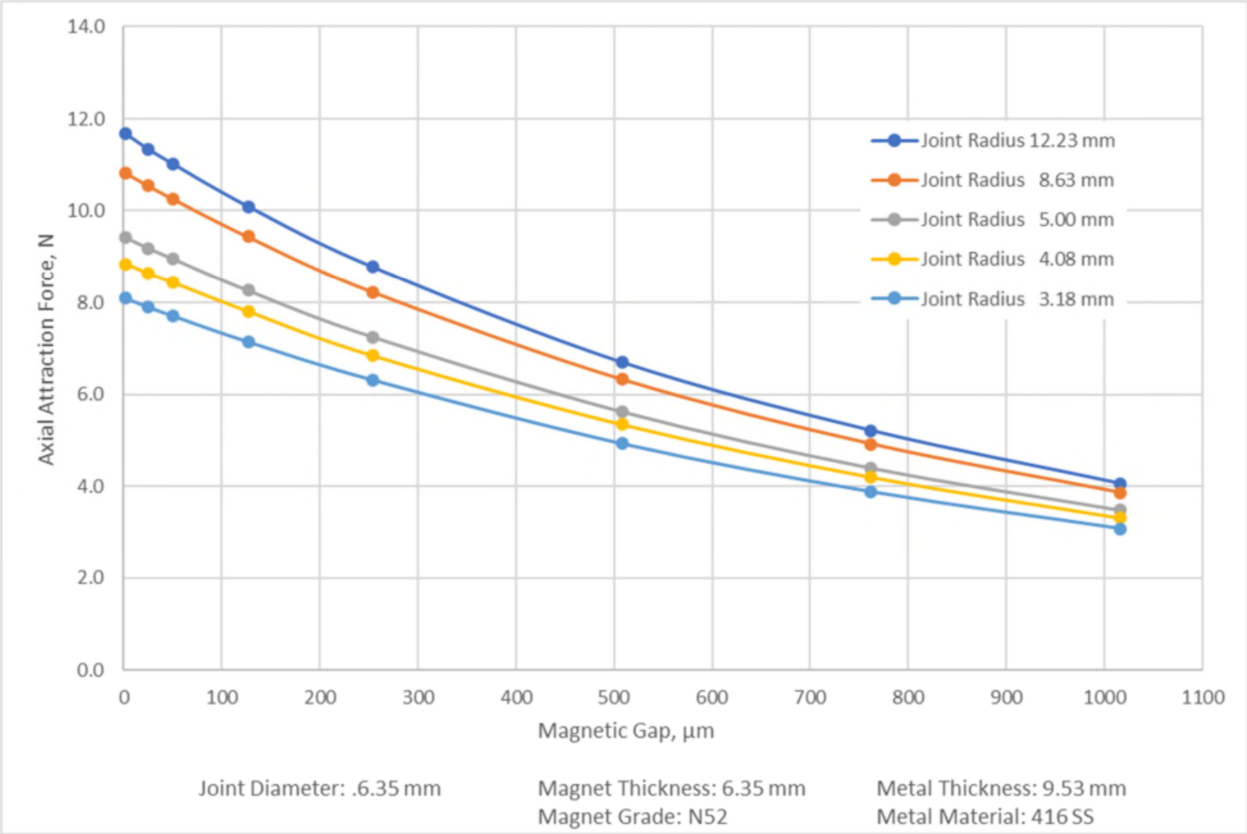

Figure 10. Axial Attraction Force as a Function of Magnetic Gap.

Conclusions

A novel magnetically coupled mechanism with a laterally unconstrained magnetic joint, and its application in tip-tilt platform actuation was introduced. A common application, optical flat mirror actuation over an extended pointing angle, was also described. The paper outlined the considerations and optimization process for the geometry of the joint components. The results of a Finite Element Analysis study on the axial attraction force within the joint were presented.

References

1. Krylov, Vladimir and Castillo, Aaron “Multi-axis Scanning Pushes Next-Generation Steering Performance.” *Laser Focus World* (September 2021)
2. Krylov, Vladimir G. *Magnetic Joint and Optical Mount Using the Same* (U.S. Patent No 10,685,771). U.S. Patent and Trademark Office.
3. Krylov, Vladimir G. *Laterally Unconstrained Magnetic Joint for Tip Tilt and Piston-Tip-Tilt* mounts (U.S. Patent No 10,830,988). U.S. Patent and Trademark Office.