

A Novel Mechanism for Implementing Multiple Collocated Spherical Joints

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Abstract

This paper presents the Spherical Joint Mechanism, a new mechanism for implementing multiple collocated spherical joints. The mechanism is designed to be strong, rigid, easy to build and have a large range of motion. Two different design concepts are presented and compared to other implementations of spherical joints previously proposed. Finally, implementation issues and potential applications of the Spherical Joint Mechanism are discussed.

1 Introduction

Many mechanisms, particularly parallel mechanisms, utilize spherical joints. A spherical joint allows three degrees of rotational freedom between two links about a single point. For some mechanisms it is advantageous to be able to collocate multiple spherical joints, i.e. to have multiple spherical joints sharing the same center of rotation. This often simplifies the mechanism kinematics (such as for the Gough-Stewart Platform) and often improves the functionality of the mechanism.

Difficulty arises, however, in constructing such spherical joints. There have been previous attempts to construct them, as will be described in Section 2. However, none of these joint constructions have been utilized in industrial applications [1]. In addition, most of these joints are unsuitable for use at very small scales because of the complexity of the parts needed to build these joints.

Some previous joint constructions have avoided the difficulty of constructing multiple collocated spherical joints by approximating them with a collection of single spherical joints with small offsets between the centers of rotation of the links. Such offsets change the kinematics of the mechanism, resulting in one of two possible problems. First, if the offsets are included in the kinematics of the mechanism, the

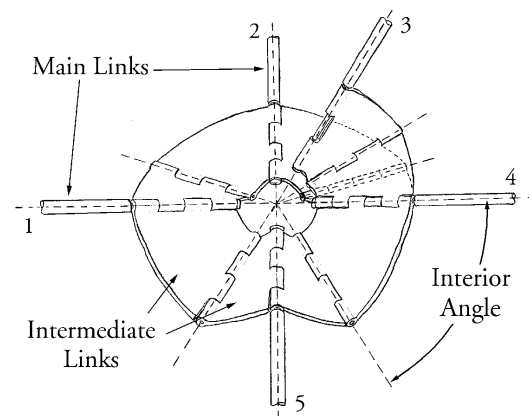


Figure 1: Diagram of Primary Design of Spherical Joint Mechanism with 5 Links.

kinematic equations may become very complex and thus very difficult to solve. Second, the offsets can be neglected, thus simplifying the kinematic equations, but resulting in errors. These errors may have a significant impact in high-precision applications, or in manipulators such as variable-geometry trusses (VGTs) that have a macroscopically serial structure resulting in the compounding of errors.

The Spherical Joint Mechanism (SJM), shown in Figure 1, is a mechanism that implements multiple collocated spherical joints. It is designed in such a way that it is anticipated to be rigid enough for use in industrial, space, medical or military applications, is easy to build, and is suitable for use on a wide variety of scales. Note that in this paper, rigidity refers to a joint mechanism's ability to rigidly impose the spherical joint constraints between the links. This paper will present two different designs of the SJM, discuss their implementations, evaluate the designs and discuss possible applications for the SJM.

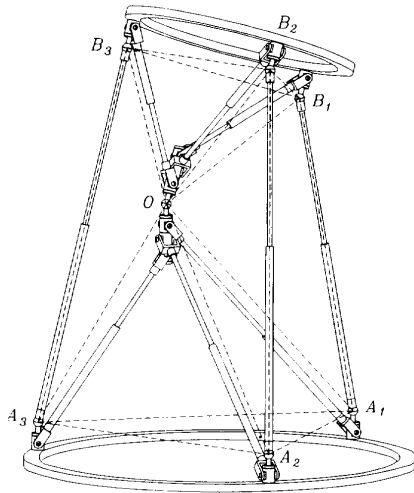


Figure 2: Parallel Mechanism Proposed by Zanganeh and Angeles that Utilizes a Spherical Connection of Six Links. [2]

2 Related Work

Previous methods of connecting multiple links to a single spherical joint have been proposed by Zanganeh and Angeles [2], Hamlin and Sanderson [3], Song and Kwon [4], and Bernier, et al. [5].

The joint proposed by Zanganeh and Angeles is shown in Figure 2.¹ Using a ball and socket and plurality of clevis joints, it allows for the connection of six links at the center of the mechanism (Point O in Fig. 2). The method of construction, however, results in significant offsets between the revolute joint axes, resulting in a connection that is not truly spherical. Additionally, this joint may have significant issues with interference.

The spherical joint proposed by Hamlin and Sanderson is shown in Figure 3. This mechanism is an improvement over Zanganeh and Angeles' joint because it produces true collocated spherical connections between several links. It can be modified to connect a various number of links and has a sizable range of motion. This mechanism, however, is difficult to construct as the dimensions and shapes of the various links in the scissor-linkages (such as link 200 in Fig. 3) must be bent at a specific angle in order to ensure proper behavior of the mechanism. Also, the strength and rigidity of this mechanism tends to be low due to the scissor-linkages. These linkages include pinned connections with short joint axes and are thus weak. Nevertheless, this mechanism has been successfully used to build VGTs in a lab environment.

¹Note that this joint was simply a sub-element of a proposed parallel manipulator and not the focus of the article.

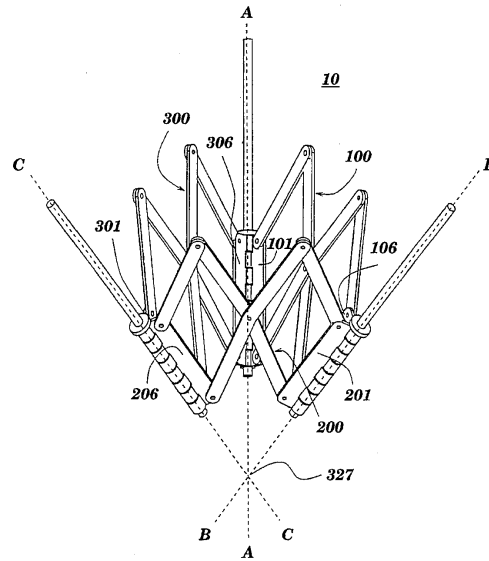


Figure 3: Joint Mechanism Proposed by Hamlin and Sanderson - U.S. Patent no. 5,657,584

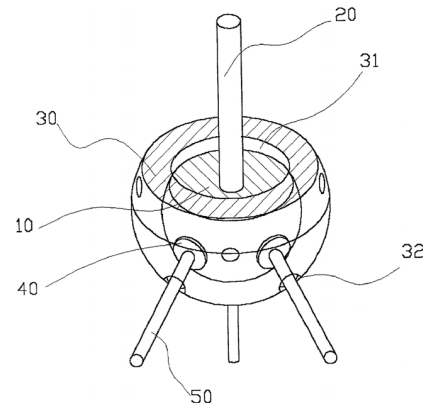


Figure 4: Joint Mechanism Proposed by Song and Kwon - U.S. Patent Application no. 20010002964

The spherical joint proposed by Song and Kwon is shown in Figure 4. This mechanism differs significantly from the previous joints in that it is based on a ball and socket joint. The addition of holes to the socket allows for more links to share connection to the ball. This construction is likely to be stronger and more rigid than the mechanism proposed by Hamlin and Sanderson, however, this joint has a very limited range of motion.

The joint mechanism proposed by Bernier et al. is shown in Figure 5. This mechanism is based on the use of a central stack of rotating disks with a shared axis of rotation. Links are connected to this stack of disks via a connecting link and two revolute joints. The axes of these revolute joints intersect the axis of

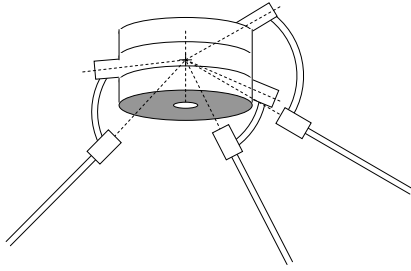


Figure 5: Joint Mechanism Proposed by Bernier et al. [4].

the disks at a central point. While this mechanism produces the desired collocated spherical connection between the links, it may have problems with rigidity due to short joint axes and a lack of closed kinematic chains. Increasing the lengths of the joint axes would increase the height of the stack of disks and may result in interference with the other links.

3 The Spherical Joint Mechanism

The Spherical Joint Mechanism, proposed here, is designed to allow the connection of multiple links to a single spherical joint, providing collocated spherical connections between the links. The SJM produces this connection between the *main links* by connecting them to each other through a series of two or more *intermediate links*, as is illustrated in Figure 1. The mechanism may be used to connect as few as two links and can be used to connect many more than the five shown in Figure 1. The main links and intermediate links are connected to each other by revolute joints, where all the joint axes intersect at a single point. This arrangement produces spherical motion of every link in the mechanism about that point of intersection. Also, the SJM allows for the connections of the links to form a closed kinematic chain. By incorporating closed kinematic chains, the rigidity of the mechanism can be significantly improved.

There are two designs of the SJM. The first design, shown in Figure 1, is the primary design of the SJM. The revolute joints are implemented with standard pinned hinges. The main links, which extend outward from the body of the SJM, are attached to the pins that pass through the corresponding hinges, thus these revolute joints actually connect three or more links to the same axis (one main link and two or more intermediate links). This allows the main links to spin freely about their respective centerlines. Because each revolute joint may be built with a relatively long axis, the joints can be made quite strong. Combining

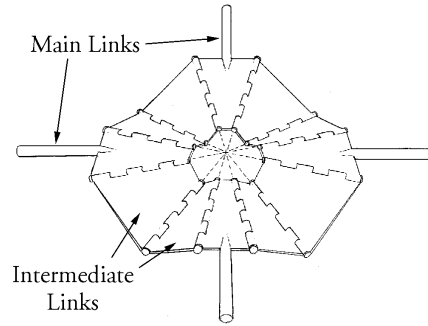


Figure 6: Diagram of Scalable Design of Spherical Joint Mechanism.

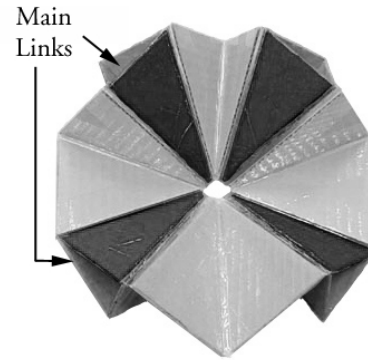


Figure 7: Prototype of Scalable Design of Spherical Joint Mechanism with 4 Links and Compliant Joints.

this with the added benefits of closed kinematic chains results in very rigid joint mechanisms.

For ease of comparison, the joint mechanisms proposed by Hamlin and Sanderson, Bernier et al. and the primary design of the SJM are contrasted in Table 1.

The second design of the SJM is called the scalable design of the SJM and is designed to be used on very small scales. A diagram of the scalable design is shown in Figure 6. A simple prototype of this design is shown in Figure 7, where each darkened link is a main link. This design differs from the primary design in the way the main links are connected to the intermediate links. The connections of the intermediate links to the main links no longer share a single axis, but rather each revolute joint connects only two links. Because of this, the SJM may be constructed using compliant joints, which are easily scalable. Additionally, the long joint axes make the SJM well suited for including compliant joints because long compliant joints are stronger and more easily constructed.

	Joint Design		
	<i>Hamlin et al.</i>	<i>Bernier et al.</i>	<i>SJM Primary Design</i>
Connection of Main Links	to each other	to central disks	to each other
Provides Space for Long Joint Axes	No	No	Yes
Closed Kinematic Chains	Yes	No	Yes

Table 1: Comparison of SJM with joint mechanisms by Hamlin and Sanderson and by Bernier et al.

4 Implementation

4.1 Primary Design

Implementation of the primary design of the SJM is fairly easy. The components of the mechanism are simple, making construction of the joint easy and inexpensive in comparison with previous joint designs.

The range of motion of the SJM depends on the maximum and minimum angles between any two main links, which are determined by the *interior angles* of the intermediate links. The interior angle of an intermediate link is the fixed angle between the link's two revolute joints (see Fig. 1). By definition an interior angle is always less than or equal to 180° . If two intermediate links are used between any two main links and the interior angle of link i is α_i , where $\alpha_1 > \alpha_2 > 0$, and θ is the angle between the two main links, then:

$$\begin{aligned}\theta_{max} &= 180^\circ - |180^\circ - (\alpha_1 + \alpha_2)| \\ \theta_{min} &= \alpha_1 - \alpha_2\end{aligned}$$

Determining θ_{max} and θ_{min} for connections using three or more intermediate links is significantly more complicated. The range of motion available for any main link at any time may be determined by simultaneously applying the previously stated range constraints between the link and all adjacent main links. An additional restriction of range is imposed by interference conditions.

Varying the interior angles of the intermediate links does not affect the collocation of the spherical joint, thus they may be altered in order to produce the desired range of motion. However, increasing the interior angles of the intermediate links increases the likelihood of interference occurring. This situation can be improved by using a low-interference version of the standard design, shown in Figure 8.

The alteration of the intermediate links prevents collision between any two intermediate links. However, the possibility still remains for interference between intermediate links and main links. Additionally, the reduction in the lengths of the joint axes will reduce the strength and rigidity of the joint.

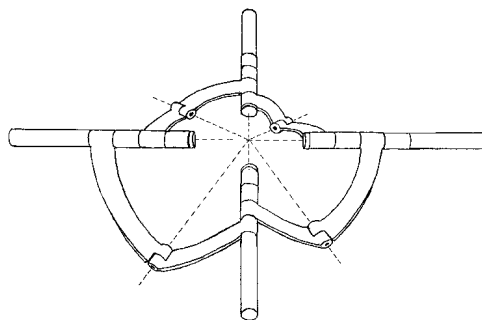


Figure 8: Diagram of the Primary Spherical Joint Mechanism Modified to Reduce Interference.

4.2 Scalable Design

The primary advantage of the scalable design (Fig. 6) is that it is well suited for construction using compliant joints. The implementation of the joints as well as the scale of the mechanism depend on manufacturing methods, thus implementation of the scalable design depends heavily on the manufacturing technology available. Several manufacturing approaches are currently being researched, including lamination and rapid prototyping. This research is being done at Georgia Tech by Dr. Allen's research group in ECE and Dr. Rosen's research group in ME, respectively. The technologies and methods for constructing these joints will not be discussed further in this paper.

Similar to the primary design, the range of motion of the scalable design depends on the interior angles of the intermediate links. However, additional constraints may be imposed by limitations of the joints themselves. For example, compliant joints built using stereolithography may have a joint range of only 90° , reducing the mechanism's range of motion. Additionally, the main links are no longer attached to pins that permit limitless rotation within the hinge, thus rotation about the centerline of a main link is limited.

Interference within the scalable design is also possible. While the primary design can be altered to

eliminate interference between connecting links, this is not recommended for the scalable design because the shortening of the joint axes would significantly weaken the joints. Interference between the intermediate links and the main links may be decreased by altering the shapes of the main links while maintaining their interior angles.

Although the scalable design is intended to be used on very small scales, it could be implemented on standard scales using traditional hinge joints. This may be preferable over the primary design if it is difficult to attach the main links to the pins of the hinge joints. However, switching to the scalable design results in a reduced range of motion due to limited range of rotation of each main link about its centerline.

5 Discussion

The SJM offers advantages in several key areas. First, the simplicity of the links and joints make the SJM easy to manufacture and assemble. The only condition that must be satisfied is that all joint axes intersect at a single point. The scalable design also allows for construction of the joint using compliant joints, as was illustrated in Figure 7, which makes it possible for the SJM to be more easily built on small scales.

The second advantage is the performance of the SJM. All main links rotate about the same point, thus the SJM does not introduce any kinematic errors. Because of the long axes of the joints and the use of closed kinematic chains, the SJM is also very strong and rigid. However, additional prototypes need to be built and tested in order to determine the load-bearing capacity of the joint. Provided that appropriate interior angles are chosen for the intermediate links, the SJM has a large range of motion, particularly in comparison to the joints proposed by Zanganeh and Angeles and by Song and Kwon.

Third, the SJM is easy to use. It is fairly simple to modify the SJM to allow attachment of additional links. Interior angles can be easily changed to vary the range of motion of the joint.

Additionally, actuation of the SJM is straightforward because of the arrangement of the joints and because all joints are revolute. In contrast, it is very difficult to actuate most other spherical joints. The advantages of the various SJM designs are summarized in Table 2.

The SJM also has some drawbacks. There is a trade-off between the range of motion of the joint and the likelihood of interference within the mechanism. In order to match the range of motion of the joint mechanism proposed by Hamlin and Sanderson, the interior angles of the intermediate links must be so large that interference is almost unavoidable. By using the low-interference design this situation improves, but

	Design Type		
	<i>Primary</i>	<i>Scalable</i>	<i>Low-Interference</i>
Multi-link Spherical Connection	Yes	Yes	Yes
Closed Kinematic Chain	Yes	Yes	Yes
Long Joint Axes	Yes	Yes	No
Compatible with Scalable Manufacturing	No	Yes	No

Table 2: Advantages of the SJM Designs.

this may compromise the rigidity of the joint. Also, as more and more links are added to the joint, the likelihood of interference increases significantly.

6 Applications

The strength and scalability of the SJM makes it a good candidate for use on a variety of scales and in a variety of environments. The SJM is well suited for use in parallel robotic mechanisms. Parallel robotic mechanisms that would require collocated spherical joints include Zanganeh and Angeles' redundant parallel manipulator [2], the 3-3 Gough-Stewart Platform [6], Mianowski's mechanism [7], Bruyninckx's variation of the Hexa robot [8], Innocenti's robot [9], the Nabla-6 robot [5], the Tetrobot [3] and variable-geometry trusses [10] (Figure 9), among others.

By allowing for rugged construction of the joints in the previously mentioned parallel robotic mechanisms, some of these mechanisms which are theoretically suitable may now become practical. Typically parallel robotic mechanisms are useful for applications that require high speed, high rigidity or high precision. The potential applications of these parallel manipulators include industrial applications such as high-precision machining, impact testing and pick-and-place tasks; medical applications such as high-precision surgical robots and haptic interfaces; and space applications such as deployable space trusses, flight simulator motion bases and VGT manipulators like the Trussarm [11].

An additional application that requires the SJM is Digital Clay [12]. Digital Clay is a device currently under development at Georgia Tech. It is a new type of computer interface that will provide a user with a tactile interaction with the virtual world. It consists of a computer controlled kinematic structure that can change its shape to represent a digital 3-D model of an object. The user may also manipulate the structure as if it was a piece of clay and the computer will

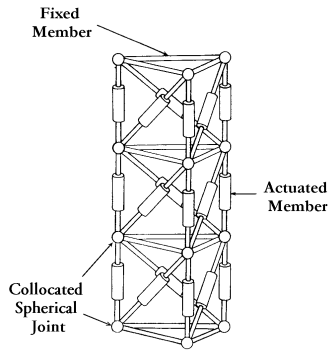


Figure 9: Example of a Variable-Geometry Truss [10].

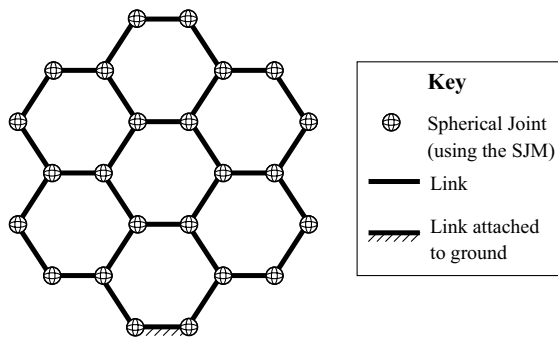


Figure 10: Example of a Kinematic Structure used in Digital Clay [12].

reflect these changes in the digital 3-D model. An example of the types of kinematic structures being considered for use in Digital Clay is shown in Figure 10. The collocated spherical joints used throughout the structure will be implemented using the scalable design of the SJM.

7 Future Work

Future development of the SJM includes 1) building and testing prototypes in order to determine the load-bearing capacity of the joint and 2) prototyping a miniaturized actuated scalable SJM. Eventually, a large number of miniaturized actuated scalable SJMs will be integrated into a kinematic structure to produce a Digital Clay device. Other potential work includes studying the effects of tolerances and joint clearances on the motion of the SJM.

8 Conclusion

This paper has presented the Spherical Joint Mechanism, a new mechanism for implementing multiple collocated spherical joints. Previous joint mechanisms

were examined, most of which suffered from high complexity, low rigidity or a limited range of motion. The SJM is strong, rigid, easy to build and has a large range of motion, thus it shows good potential for use in a variety of applications.

9 Acknowledgements

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