Research Article

Hexasphere—Redundantly Actuated Parallel Spherical Mechanism as a New Concept of Agile Telescope

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Received 1 June 2009; Accepted 11 January 2010

Academic Editor: Alberto J. Castro-Tirado

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The paper deals with the description of a new concept for a spherical mechanism for agile telescopes. It is based on redundantly actuated parallel kinematical structure. Due to the three times overactuated structure and application of several further innovative concepts, the Hexasphere achieves the movability of ± 100 degrees. This enables the use of a Hexasphere as the basis for mounts of telescopes. Such telescopes can be optimized for minimum weight or for maximum dynamics. The proposed mechanism is expected to play a role in novel robotic telescopes nowadays used in many fields of astronomy and astrophysics, with emphasis on automated systems for alert observations of celestial gamma-ray bursts.

1. Introduction

There are many mechanisms for the realization of spherical motions. Spherical mechanisms which enable the rotation and orientation of an object in the space are used for many important operations. They are in the mechanisms of swivel heads with spindles for machine tools that create the basis of an absolute majority of machine tools for 5 axes machining. The assemblies of telescopes, that is, the mechanisms for their motion, are also spherical mechanisms. Another group consists of mechanisms for rotation of different antennas. Many applications of spherical mechanisms are for the pointing of optical beams.

The absolute majority of spherical mechanisms are based on the Cardan hinge. Its advantage is high movability, often $\pm 90^\circ$. The first basic disadvantage of Cardan hinges as serial kinematical structures is that they consist of a sequence of successive rotational motions. This leads to the necessity that the subsequent rotations must carry the drive with and

thus increase the mass of the construction. Besides that, the frame of the construction is loaded detrimentally by bending. The consequences are a disadvantageous ratio between mass and stiffness and the smaller dynamic capabilities of the mechanism. The addition of errors in the chain of partial motions leads to a lower positioning accuracy. The second basic disadvantage of Cardan hinges is that the zenith position is singular, making it impossible to carry out a continuous trajectory between all positions in the workspace.

All of these problems were circumvented by the adoption of parallel kinematical structures [1] where the only form of loading is either compression or stress, all motors are situated on the machine frame, and the length of error chains with summed up errors is significantly lower. The disadvantage of simple parallel kinematical structures is that their workspace is limited by singular positions and collisions, the mostly used spherical joints acquire lower stiffness when compared to sliding or rotational joints and nonlinear kinematic transformation between motors and the

FIGURE 1: Telescope HPT Cerro Armazones, Chile.

FIGURE 2: Parallel spherical mechanism.

end-effector requires a short sampling period, in order to achieve required accuracy.

The mounts of traditional telescopes both on earth and in orbit (on satellites) are based on the Cardan mechanism. The spherical mechanisms based on Cardan mount as serial mechanisms suffer from the zenith singularity and large mass because of frame loading by bending. This can be improved by mechanisms based on parallel kinematical structure (e.g., Hexapod) where the loading is changed to tension-compression. The recently built hexapod-based telescope HPT (Figure 1) has only 1/5 of the mass of a traditional telescope but can tilt by only $\pm 47^\circ$ before it reaches the singular positions and would collapse [2]. This limitation can be significantly extended if the parallel kinematical structure is redundantly actuated [3, 4]. Based on this idea, a new spherical mechanism suitable for telescope mounts—named Hexasphere—was proposed and a functional kinematical lab model was built. It has demonstrated that Hexasphere

FIGURE 3: Hexasphere kinematical structure.

FIGURE 4: The dexterity of spherical mechanism from Figure 2.

FIGURE 5: The dexterity of Hexasphere.

FIGURE 6: Design features of Hexasphere.

can reach the workspace at ± 100 degrees. The experience with parallel kinematical structures is that it can achieve high stiffness and agile dynamics with low masses. The only drawback of limited workspace, due to the kinematical singularities, can be removed by redundant actuation and has been demonstrated by Hexasphere.

2. The Hexasphere Concept

The initial motivation came from [5] where the spherical mechanism in Figure 2 was proposed. The claim was that the problem with singularities (dexterity) had been solved. This structure has been analyzed for the dexterity.

The position of the platform in the space is described by the coordinates q , and the positions of the drives (extensions of struts) are described by the coordinates z . These coordinates are constrained by the constraints

$$f(q, z) = 0. \quad (1)$$

The dexterity is defined as

$$D = \frac{1}{\text{cond}(J_z^{-1}J_q)}, \quad (2)$$

where J_z and J_q are the Jacobians of the constraints (1) with the respect to the coordinates z and q . The dexterity ranges from 0 (the worse value corresponding to the singularity) to 1 (the best value). It expresses the transfer between the input-output velocities and the input-output forces of the mechanism.

Using this approach, the dexterity for the mechanism in Figure 2 has been computed. The range of the dexterity is 0.0065 to 0.6307 (Figure 4). It is nonzero and the workspace is free of singularities but the dexterity changes over a large interval (a factor of a hundred) and the minimum values are very close to zero. It is disadvantageous because the dexterity describes the ratio between the driving force and the acting forces in the end-effector.

To solve these problems, the concept of a Hexasphere [6] has been proposed (Figure 3). The principle of redundant actuation [1] has been applied in order to improve the dexterity. The redundant actuation alleviates the problems associated with parallel kinematics: singularities do not

occur, surprisingly the collisions can be limited, the stiffness and dynamics are significantly increased, kinematic accuracy is improved, and online calibration is possible. The result is that redundantly actuated parallel kinematical structures are functionally equivalent to machines with serial kinematical structures but have significantly improved mechanical properties (stiffness, dynamics, accuracy). This has been successfully demonstrated on the machines Trijoint 900H [7] and Sliding Star [4] for Cartesian translational motion. The remaining kinds of mechanisms with serial kinematical structure are the spherical mechanisms based on Cardan hinges. Although one of the most successful applications of parallel kinematical structures is the parallel swivel head for 5 axes machining, it reaches only limited movability. Finding fully functional equivalent of Cardan hinges with movability $\pm 90^\circ$ using parallel kinematical structures has been an open challenge for a long time.

The concept of a Hexasphere has been used as the basis of the mechanism from Figure 2 and it uses the principle of redundant actuation. The number of redundant struts has been increased. Hexasphere is a combination of Hexapod for actuation and a platform suspension on a passive spherical joint. Hexasphere is three times redundantly actuated. The influence of the high degree of actuator redundancy is very positive on the dexterity. The dexterity of Hexasphere has been analyzed by the same approach: its results are in Figure 5. The dexterity ranges only in the interval from 0.33 to 0.65. The dexterity changes in the whole workspace only twice and its values are quite high. The required actuation forces are just 2-3 times higher than the acting forces in the end-effector.

3. Design of Hexasphere

The mechanism of Hexasphere has the open challenge of parallel spherical mechanism with large tilting angles positively closed. It demonstrates that the redundantly actuated parallel kinematical structure enables the spherical motion now with movability $\pm 100^\circ$ and preservation of all advantages of parallel mechanisms. The new solution principles that enable to create a Hexasphere are the following. The platform is connected to the frame by a central spherical joint. Hence the mechanism has only 3 degrees of freedom and for the motion it would suffice just 3 actuators. However, they enable the motion just in small extent of angles because for large motions the singular positions occur when the platform acquires additional uncontrolled degree of freedom and collapses. Therefore, the platform is suspended on 6 struts. The result is not only the removal of singularities but also very good dexterity in the whole workspace. Another important principle is that the struts are placed on shanks due to which the collisions between the struts and the platform do not happen for large rotations (Figure 6). The other dimensions must be also adjusted accordingly.

Besides the mentioned solution principles of a Hexasphere, the usage of many innovative components was necessary. They are above all the spherical joints with substantially increased mobility. They are realized either

FIGURE 7: Two variants of spherical joint with significantly increased movability.

FIGURE 8: Different kinds of strut actuation.

FIGURE 9: Strut concept of functional model.

purely mechanically (but at least with measurement of inner joint motion for calibration if not even with brakes) [8] or by electromagnetic spherical joint (Figure 7) [9].

The struts of Hexasphere can be realized by different ways. They are depicted in the Figure 8. The struts can be with variable length (just extending or telescopic), with fixed length on sliding carriage, or based on robotic arm with rotational joints. The chosen concept of struts for the

manufactured functional model is the strut fixed length on sliding carriage (Figure 9). Using these principles, the design of the functional model of the Hexasphere was carried out and the functional model was manufactured (Figure 10).

4. Applications of Hexasphere for Telescopes

Hexasphere is a new spherical mechanism that can be advantageously used for the design of new telescope mounts. Two such possible concepts are shown in Figure 11. The mechanisms based on Hexasphere concept can be optimized for minimized weight or for maximized dynamics.

The other important property of Hexasphere is the self-calibration that is redundantly actuated and therefore redundantly measured, that is, the capability to determine the dimensions of the whole mechanism just using the internal sensors without any external device. This can be used for online compensation of thermal deformations.

The proposed system is expected to play a role in novel robotic telescopes nowadays used in many fields of astronomy and astrophysics, with emphasis on automated systems for alert observations of celestial gamma-ray bursts. In these systems, there is a need for a fast movability to a sky position which cannot be predicted and is announced by satellite alert systems based on satellites carrying gamma-ray bursts monitors. This position can be hence anywhere on the (visible) sky. The response as fast as possible is essential here, as in some cases prompt optical emission related to gamma-ray burst was observed simultaneously with the gamma-ray burst. The Hexasphere can be considered both for small as well as large telescopes, with still some possible application for wide-field sky monitors including all-sky guided cameras. Here the Hexasphere would be optimized for dynamical applications.

The other applications of a Hexasphere might be the automated telescopes/antennas placed in satellites or Moon or other planets where the weight of the Hexasphere would be optimized.

FIGURE 10: Engineering design and functional model of Hexasphere.

FIGURE 11: Possible applications of Hexasphere as mounts of telescopes.

For the future, it is planned to design, develop, and test a prototype carrying small robotic telescopic system/camera in order to exploit and to test its performance in this application in more detail.

5. Conclusions

The paper has described the new spherical mechanism Hexasphere suitable for mounts of telescopes. The movability of Hexasphere is ± 100 degrees. The mechanisms based on the Hexasphere concept can be optimized for minimized weight or for maximized dynamics.

The proposed system is expected to play a role in novel robotic telescopes nowadays used in many fields of astronomy and astrophysics, with emphasis on automated systems for alert observations of celestial gamma-ray bursts.

Acknowledgments

The authors appreciate the kind support by MSMT project MSM 6840770003, GACR project 101/08/H068, and the Czech Technical University Media Lab Foundation. Rene Hudec acknowledges support by the Grant Agency of the Czech Republic, Grant 102/08/0997.

References

- [1] M. Valášek, “Redundant actuation and redundant measurement: the mechatronic principles for future machine tools,” in *Proceedings of the 3rd International Congress on Mechatronics (MECH2K4 '04)*, pp. 131–144, Praha, Czech Republic, July 2004.
- [2] M. Hustý and H. Eberharter, “Kinematic analysis of the hexapod telescope,” in *Proceedings of the 2nd Workshop on Computational Kinematics*, F. Park and C. Iurascu, Eds., pp. 269–278, Seoul, South Korea, 2001.
- [3] M. Valasek, Z. Šika, V. Bauma, and T. Vampola, “The innovative potential of redundantly actuated PKM,” in *Proceedings of the 4th Chemnitz Parallel Kinematics Seminar (PKS '04)*, pp. 365–384, 2004.
- [4] M. Valášek, V. Bauma, Z. Šika, K. Belda, and P. Piša, “Design-by-optimization and control of redundantly actuated parallel kinematics sliding star,” *Multibody System Dynamics*, vol. 14, no. 3-4, pp. 251–267, 2005.
- [5] R. Kurtz and V. Hayward, “Multiple-goal kinematic optimization of a parallel spherical mechanism with actuator redundancy,” *IEEE Transactions on Robotics and Automation*, vol. 8, no. 5, pp. 644–651, 1992.
- [6] M. Valasek and M. Karasek, “Kinematical analysis of hexasphere,” in *Proceedings of the Conference on Engineering Mechanics*, pp. 1371–1378, Praha, Czech Republic, 2009.
- [7] F. Petru and M. Valasek, “Concept, design and evaluated properties of TRIJOINT 900H,” in *Proceedings of the 4th Chemnitz Parallel Kinematics Seminar (PKS '04)*, pp. 569–584, 2004.
- [8] D. Sulamanidze, *Spherical joints with increased mobility*, Ph.D. thesis, FME CTU, Prague, Czech, 2007.
- [9] M. Valášek, F. Petrů, and J. Zicha, “Magnetic spherical joint,” Patent Pending PV 2008-2058.