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A review of spherical motion generation using either spherical parallel manipulators or spherical motors

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In this paper the authors review spherical motion generation by means of parallel manipulators or spherical motors. The state-of-the-art of spherical-motion-generator kinematics, dynamics, design optimization and novel spherical mechanisms with emerging applications are reviewed. New research problems and future developments are discussed.

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1. Introduction

Spherical motion occurs frequently in mechanical systems like robotic wrists, orienting mechanisms, exoskeletons, etc [1–5]. Spherical motion finds applications in many areas such as solar panels, cameras, telescopes, machine tools, rehabilitation robots, humanoids and exoskeletons.

A rigid body undergoes spherical motion when one of its points remains fixed, while all others move. In a mechanical system (robots, spherical linkages), spherical motion refers to the rotation about one common point of all moving bodies of the system, or subsystem, as the case may be, called the center of rotation. Spherical motion is one of the 12 subgroups of the rigid-body displacement group $\mathcal{D}$ [6,7]. One specific motion is characterized by one axis of rotation passing through the center of rotation and a given angle. The dimension of the spherical motion subgroup, i.e., the number of variables required to characterize one given motion of this subgroup, is three. Within the rotation subgroup there are two subsets of displacements, lacking the group property. These are (*i*) pointing [8] and (*ii*) pan-tilting [9,10]. In the two cases, the two intersecting axes of rotation lie at right angles. In (*i*) the pitch axis is horizontal, the tilt axis making a variable angle of pitching with the vertical. In (*ii*) the pan axis is vertical, intersecting the tilt axis, which is horizontal. The dimension of both subsets is two.

Spherical motion can be generated with a variety of principles and realizations, as shown in Fig. 1. From the mechanism perspective, a conventional implementation of spherical motion is the industrial wrist designed with serially connected links. Alternatively, spherical motion can be generated by SPMs.[1] Spherical motion can also be generated by means of spherical actuators. Such actuators include spherical motors and internal or external actuated spheres that are commonly used in spherical robots [11,12]. A spherical-motion system can have either one single degree of freedom (dof $= 1$) or multiple dof (dof $= 2$, or 3). For example, a spherical four-bar linkage has one dof, while a pointing device [13] or a pitch-roll wrist [4] has two. Most SPMs and spherical motors and robots [14] have three dof.

In this paper we focus on multi-dof spherical motion generation by means of spherical parallel kinematics machines (PKM), besides spherical motors. Extensive studies have been reported on spherical parallel manipulators, covering workspace modeling, dexterity evaluation [15], design and optimization [16,17], singularity analysis [18], and type synthesis [19], among others. In spite of the extensive study of SPMs, only a paucity of works provide a review in terms of spherical motion generation. A brief review of wrist joints was provided by Canfield [20]. A recent review on wrist joints with their applications in prosthetic and robotic wrists was reported by Bajaj et al. [1]. A comprehensive review of research activities up to date and a perspective into research topics ahead is necessary.

Our intention is to provide a comprehensive review of the research works on spherical motion generators (SMGs)[2] up to date. The objective is to review thoroughly the research and development of SMGs, upon which some future research directions are identified and suggested. The review covers kinematics, dynamics, control, design optimization and novel spherical mechanism design. A few new research problems and future developments are discussed. The research work on spherical motors is also reviewed to provide a broad coverage on spherical motion generation.

2. SPM kinematics

Spherical parallel manipulators pertain to a special type of PKMs, whereby the end-effector or the moving platform rotates about either a physical center or a virtual (remote) center. They are intended to provide three degrees of freedom of pure rotation.

The realm of spherical parallel manipulators is well studied. The earliest research work on spherical parallel manipulators can be dated back to 1989 when Gosselin published his research results on the kinematic design and optimization of SPMs [26]. In the same year, Craver reported also a paradigm SPM in his thesis [27]. The first prototype, called the Agile Eye, was constructed by Gosselin and his research group at Laval University, Canada. An extension of the Agile Eye, called the Agile Wrist, was prototyped by Angeles under structural design optimization [22,23]. The design of a spherical wrist with parallel architecture intended for its application to the vertebrae of an eel robot was reported by Chablat and Wenger [28]. Fig. 2 shows four examples of SPMs.

The kinematics of SPMs is fundamental to their analysis, design and control. Prior to reviewing the kinematic analysis, design optimization and stiffness modeling of SPMs, we briefly describe their basic concepts, taking the 3RRR SPM as an example.

Fig. 3 depicts the kinematic chain of the 3RRR SPM. It has three identical limbs, each forming an open, four-link, spherical chain, all three sharing one common base platform (BP) and one common mobile platform (MP). The axes of all joints intersect at one common point O, the *center of the mechanism*.

The same figure shows the notation for the formulation. In the figure, the orientation of the axes of all joints is denoted by the unit vectors $\mathbf{u}_i$, $\mathbf{v}_i$, and $\mathbf{w}_i$, for $i = 1, 2, 3$. A coordinate system is selected such that its origin is located at the center of the mechanism, while the z-axis is normal to the plane of the BP bottom triangle, pointing upwards. The y-axis is normal to

[1] This acronym and others are defined in Fig. 1.

[2] The same acronym is found in the robotics literature to denote *Schönflies-motion generator*, with four dof, as such systems fall outside of the scope of this paper.

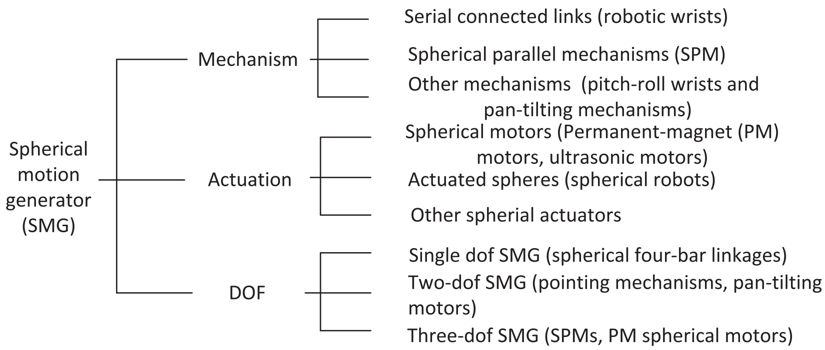


Fig. 1. Classification of spherical motion generators.

Fig. 2. Prototypes of spherical parallel manipulators, (1) the Agile Eye [21], (2) Agile Wrist [22,23], (3) a tele-operation haptic device [24], (4) a 3UPU wrist [25].

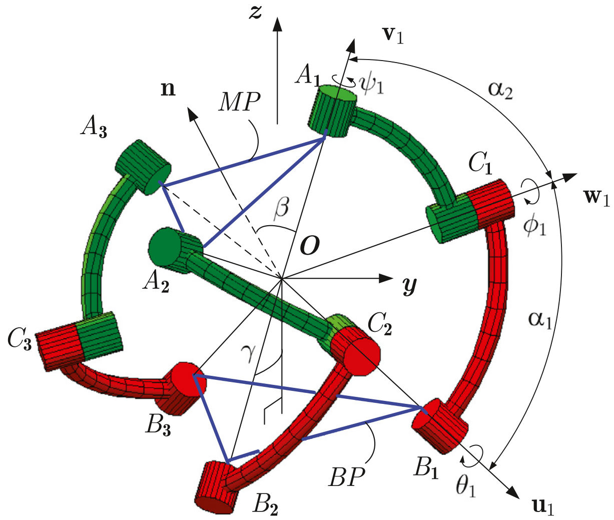


Fig. 3. Typical 3RRR SPM with parameters for kinematic analysis.

the z-axis and lies in the plane made by the z-axis and line $\overline{OB}_1$. Moreover, the dimensions of the proximal links, connected to the base platform, and the distal links, connected to the mobile platform, are angles α_1 and α_2, respectively.

Let the input joint angles be θ_i, $i = 1, 2, 3$, measured from the plane made by the z-axis and $\overline{OB}_1$ to the plane of a proximal link. For the closed chain of the spherical parallel robot, we have

$$\mathbf{w}_i \cdot \mathbf{v}_i = \cos\alpha_2, \quad i = 1, 2, 3 \tag{1}$$

Eq. (1) is one constraint equation for the SPM. The Jacobian matrix can be derived from these relations. The forward-kinematics and inverse-kinematics problems are solved subsequently. While the solution of the latter is straightforward, that of the former is challenging. Different approaches have been developed to solve the forward kinematics, as reviewed below:

- *Using the three unit vectors of the mobile platform as unknowns*
  In some works, the three unit vectors of the mobile platform are used as unknowns [3]. This means that the problem involves nine unknowns, the three vector-components, one triad per vector, subject to three unit-norm conditions. Besides Eq. (1), additional equations are needed, which are
  $$\mathbf{v}_i \cdot \mathbf{v}_j = \cos\alpha_{ij}, \quad i, j = 1, 2, 3, \qquad i \neq j \tag{2}$$
  where α_{ij}, a known quantity, is the angle between the axes of the ith and the jth distal joints. Moreover, vectors $\mathbf{v}_i$ obey the conditions
  $$\| \mathbf{v}_i \| = 1 \tag{3}$$
  Eqs. (1)–(3) form a system of three linear and six quadratic equations in vectors $\mathbf{v}_i$, from which possible values of $\mathbf{v}_i$ can be found. Upon computation of the three vectors, the rotation matrix $\mathbf{Q}$ carrying the MP from its reference to its current orientation can be uniquely determined. This approach is straightforward; however, the Bezout number of the system of equations is as high as 64 ($= 2^6$), which implies a high computational complexity.
- *Using the Euler angles of the mobile platform as unknowns*
  The unit vectors $\mathbf{v}_i$ are expressed by
  $$\mathbf{v}_i = \mathbf{Q}\mathbf{v}_i^* \tag{4}$$
  where $\mathbf{Q}$ is the rotation matrix and $\mathbf{v}_i^*$ the pre-image of $\mathbf{v}_i$ under $\mathbf{Q}$. If the orientation of the mobile platform is described by the array of Euler angles $\boldsymbol{\varphi} = [\varphi_1, \varphi_2, \varphi_3]^T$, then the rotation matrix is
  $$\mathbf{Q} = \mathbf{Q}(\boldsymbol{\varphi}) \tag{5}$$
  the system of three Eq. (1) thus having three unknown Euler angles. Gossselin et al. [29] carefully selected the coordinate system fixed to the mobile platform to simplify the equations: the z-axis was aligned with the shaft axis of a joint connecting the mobile platform and a distal link, for which one Euler angle is identical to the arc subtended by the mid-curve of the distal links. The solution was found via the roots of an octic. It is noted that the approach using Euler angles as unknowns has its drawback, as Euler angles, not being invariant, are prone to spurious singularities.
- *Using the actuated-joint angles as unknowns*
  This approach resorts to the joint angles of one of the three limbs [30], i.e., limb 1, for the expression of unit vectors $\mathbf{v}_i$. In this way, the vectors are functions of the joints angles, i.e.,
  $$\mathbf{v}_i = \mathbf{R}_i(\theta_1, \phi_1, \psi_1)\mathbf{v}_i^* \tag{6}$$
  where the unknowns are still the above mentioned Euler angles.
  For the forward-kinematics problem with θ_1 known, only two unknowns per limb are present. By combining Eq. (1) for limbs 2 and 3, a system of two equations for two variables is established. These equations lead finally to an octic as well.
- *Using intermediate angles as variables*
  Unlike the above methods, which directly rely on the single-limb Eq. (1), Bai and Angeles [31] proposed a method resorting to the input-output (I/O) equation of spherical four-bar linkages [32], upon noticing that this equation is actually a combination of two closure equations of single individual limbs. Thus, the direction solutions are the intermediate angles. In this way, loop equations with compact coefficients can be expected, which lead to simpler calculations and an enhanced robustness of the displacement analysis. The underlying method developed is applicable to SPMs of the 3RRR type as well as to their 3UPU counterparts, the characteristic polynomial being octic [31,33].

Alternative approaches have been developed to solve the forward-kinematics problem. For example, Huang and Yao [30] reported a method in which the direction cosines of each joint axis are introduced as functions of the actuated joint variables. An algorithm for solving the direct kinematics of parallel spherical mechanisms taking advantage of the subdivision and convex-hull properties of the polynomials was proposed by Bombin et al. [34].

The difference in the above methods notwithstanding, a 3RRR SPM admits at most eight solutions, as reported in the literature [29,35]. All solutions stem from the roots of a *minimal* eighth-order polynomial, what is known as the robot *characteristic equation*.

The aforementioned forward-kinematics formulations enable the kinematic design and analysis of SPMs applicable to some special cases. Gosselin and Lavoie studied different kinds of spherical parallel manipulators. Some special configurations of 3RRR SPMs are considered, including co-planar actuators and collinear actuators [36]. Alizade et al. [37] investigated

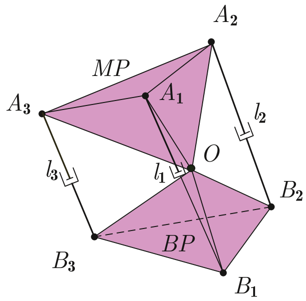


Fig. 4. Kinematic chain of a 3UPU spherical parallel robot.

a spherical parallel robot with revolute joints, wherein a specific architecture was considered that lends itself to closed-form solutions. Bai et al. studied the kinematics of a SPM with co-axial inputs [38].

In addition to the 3RRR SPMs, there are a few other types of SPMs, such as 3UPU, 3PSS, 3RRS, 3URC [39–42], and 3CPU [43]. For a SPM of the 3UPU type, as shown in Fig. 4, Innocenti and Parenti-Castelli [35] derived a system of two equations, one octic, one linear. In the work of Ji and Wu [33], the forward kinematics of spherical parallel robots with prismatic joints and identical pyramids was studied by resorting to three closure equations. Zhang and Dai studied kinematics of reconfigurable SPMs [44]. An overconstrained SPM inspired by origami was reported by Wei and Dai [45].

It is noted that the complexity of the kinematic analysis depends heavily on the rotation representation. Given the variety of rotation representations [46–49], studies on the kinematics of spherical manipulators with different rotation representations are needed. We recommend *invariant representations*, which offer *computational robustness*[3] over their alternatives.

3. Performance analysis of SPMs

A major function of a SPM is to provide a prescribed orientation to its end-effector or to its moving platform, as the case may be. Many performance indices have been introduced for design and analysis. The mostly studied indices are workspace, singularity, dexterity, and stiffness, among others.

3.1. Workspace and singularity analyses

Workspace, in the context of SPMs, refers to a region in configuration space representing all feasible orientations of the mobile platform of a SPM.

Up to date, modeling and analysis works on SPMs, under different approaches, have been reported to address workspace analysis [17,26,50,51]. Gosselin and Angeles [26] conducted workspace analysis using the linear invariants (LI) of the rotation matrix to explore the workspace of a single limb and then expanded the analysis to the entire manipulator; an orientational representation called “tilt-and-torsion angles” was used in the workspace modelling proposed by Bonev and Gosselin [50]. A notable numerical approach was reported by Yang and Chen [51], where a solid sphere representing all orientations is partitioned equivolumetrically for a high calculation accuracy.

A method of workspace and singularity analyses was reported by Bai et al. [38], in which the orientation of a SPM is described by Euler parameters to avoid any possible formulation singularity [52]. The adoption of Euler parameters in the SPM kinematics leads directly to polynomial equations. It is noted that the rotation equations with Euler angles can also lead to polynomial equations, via what is known as the “tan-half identities”. Other works of SPM kinematic analysis with Euler parameters can be found in literature [53,54].

In a recent paper by Li et al. [8], the kinematics of *pointing*, one subset of the spherical motion subgroup, was studied. The authors discussed the special features of the kinematics of pointing, that of spherical motions at large, and visualized the workspace of interest, namely, a surface in three-dimensional (3D) space, for different means of pointing description, including (a) LI; (b) Euler–Rodrigues parameters and (c) the natural invariants, i.e., the unit vector parallel to the axis of rotation and the angle of rotation.

The challenges of SPM workspace analysis are regarded from two perspectives. To begin with, the workspace is related to the presence of multi-loop closed kinematic chains: workspace analysis often yields high-order polynomial equations, which are not only functions of the orientation of the end-effector, but also functions of the input angles, i.e., the joint variables.

Furthermore, the workspace is closely related to the parameterization of the rotation. Representations of the latter include *Euler angles, pitch-yaw-roll angles, Euler parameters*, a.k.a. *quaternions, linear invariants*, etc. The nature of the parameterization certainly dictates the size of workspace-volume calculation. For the same reason, analysis of the singularity of SPMs is closely related to the rotation representation. Different rotation parameters will lead to different singularity loci [55,56]. Dependence between parameterization and performance indices is a topic calling for an in-depth study.

[3] That is, independence of the choice of frame.

3.2. Stiffness analysis

The stiffness of a SPM has a significant influence on its performance in terms of motion accuracy and dynamic response. The flexibility of the links of the SPM can affect the orientation of the mobile platform, thus affecting its precision. In some designs where no physical center of rotation, as in a ball-and-socket joint, exists, the center of the MP will shift away from the center of the base platform, by virtue of link compliance. This will lead to error in the positioning accuracy.

Gosselin reported a stiffness modeling method for parallel manipulators [57] by considering both actuator compliance and the manipulator Jacobian. Liu et al. [17] extended this method to 3RRR SPM. Recently, the stiffness analysis of a 3RRP SPM was conducted on the basis of strain energy and Castigliano's theorem, while ignoring the influence of the passive joints and strain energy due to shear forces [58]. As SPMs are widely used as orientating devices, most stiffness analyses were limited to the orientational deformation. In the work of Wu et al. [59], the platform center shift along with the orientational deformation was studied by the virtual-spring method in connection with Castigliano's theorem to calculate the limb stiffness in SPMs. Zhang, et al. develop a dynamic model for frequency analysis of a 3RPS SPM [60].

3.3. Design optimization

The design optimization of SPMs has attracted significant attention with numerous publications available. A preliminary kinematic optimization was studied to obtain manipulators for isotropic postures [36]. A kinematic optimization with multiple goals was conducted by Kurtz and Hayward [61] for a 4-SPS parallel spherical mechanism, for which dexterity, actuating forces, and the uniformity of the dexterity were considered. Stiffness optimization of SPMs was reported by Liu et al. [17]. Kinematic optimization was conducted for a prescribed workspace by Bai [62] to achieve an optimum design for dexterity. Multi-objective optimization, considering a global conditioning index, workspace, dynamic torque, etc., was reported by Wu et al. [63]. Other SPM optimization works can be found in the literature [64–66].

4. Dynamics modelling and control

Compared with the extensive work on the kinematics of SPMs, their statics/dynamics has received scarce attention. Gregorio presented the statics of a 3UPU wrist in combination with singularity analysis [41]. Staicu [67] used the principle of virtual work to derive the inverse dynamics of the Agile Wrist [23], in which recursive matrix relations for kinematics and dynamics were established. Staicu also studied the dynamics modeling of 3UPS/S SPMs [68].

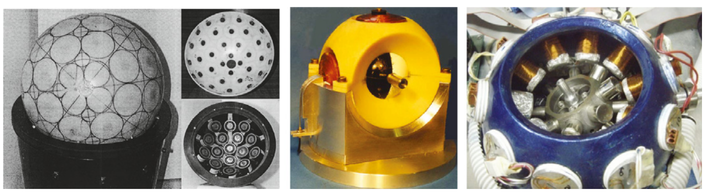
Wu, et al. developed a dynamics model with the classical approach of Lagrange multipliers, which takes all the mobile components into consideration, to calculate the power consumption effectively [63]. The equation of motion for the SPMs is modeled with the motion characteristics, namely, all the bodies rotating about one fixed point (center of rotation) [63]. The model thus derived can be used either to assess the dynamics performance or to support design optimization.

Gallardo et al. [69] formulated dynamics models for parallel manipulators, including spherical ones, based on the theory of screws and the principle of virtual work. The authors included the case study of a two-dof parallel spherical mechanism [69]. Other works on dynamics modeling can be found in the literature [70,71].

The control of SPMs, up to date, is limited to kinematic, or position control [66,72]. The control of a SPM prototype actuated by three linear motors was reported by Callegari et al. [73], in which several position control schemes were compared. A control method to achieve an optimal torque distribution for a redundant 3RRR SPM was reported by Saafi et al. [74].

5. Spherical motors

Spherical motors form a class of spherical-motion generators, capable of producing multi-dof rotations in one driving unit [75]. A spherical actuator has a compact structure, high energy density, low moment of inertia and rapid response. Williams et al. designed the first two-dof spherical induction actuator in the 1950s [76]. Since then, various designs and operating principles of spherical actuators have been investigated for decades [77–80]. Some prototypes are shown in Fig. 5.



(a) (b) (c)

Fig. 5. Prototypes of spherical actuators: (a) Spherical stepper motor [81]; (b) PM spherical motor [82]; (c) Spherical wheel motor [83].

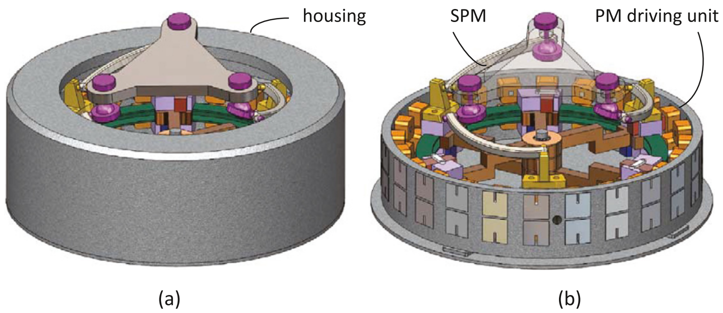


Fig. 6. An integrated spherical motion generator combining electro-magnetic driving and a co-axial input SPM, (a) design of the SMG, (b) internal view with the housing removed [95].

Spherical motors can be constructed as spherical ultrasonic motors or PM[4] motors. The former utilize ultrasonic vibration to drive the spherical motor, which can be designed with a compact size and a large range of motion [84–86]. While friction drives bring in the advantage of a fast response, they compromise durability and positioning accuracy.

A variable-reluctance (VR) spherical motor was proposed by Lee et al. [83]. In the VR spherical motor, a number of coils are evenly housed in a hemispherical stator. The permanent-magnet poles are distributed on the rotor surface. The rotor is connected with the stator by means of gimbals. The output shaft can freely roll on the gimbals. The rotor produces three-dof rotational motion by varying the current inputs at the stator coils. However, the high inertia and the additional friction between rotor and slide track seriously influence the system performance.

Chirikjian et. al. [81] designed a spherical stepper motor with cylindrical PMs placed on the inside surface of a hollow plastic sphere. Differing from the symmetric arrangement, the stator coils with soft iron cores are housed in a spherical cap in order to obtain a wide range of motion, as per Fig. 5(a).

Wang et al. [82] developed a three-dof PM spherical motor, as shown in Fig. 5(b). The spherical rotor is constructed by two pairs of rare-earth magnet quarter-spheres. Four sets of windings are housed within the spherical stator, which help to simplify the torque model and the controller design. As the rotor turns within the spherical stator on a low-friction surface coating, however, the wear and tear of the coating, that grows over time, cannot guarantee the stability of the system.

Lee and Son developed a spherical wheel motor (SWM) [87,88]. The SWM consists of 16 cylindrical PMs and 20 stator air-core coils, as illustrated in Fig. 5(c). To investigate the electromagnetic fields and torque of the PM-based devices, a distributed multipole model (DMP) was introduced, derived from the concept of magnetic dipole. A two-dof orientation sensor was used to measure the orientation of the spherical wheel motor in real time [89].

Spherical motors, as a new type of motion generators, have the advantage of compact size, fast response and zero backlash, all present in mechanical transmissions. They, however, show in general some limitations, such as low precision, relatively low output torque, and complex control requirements. Intensive research has been devoted to improving the performance of PM spherical motors. Yan et al. extended the PM distribution in 3D magnet arrays, while using spherical harmonics (SH) to analyze the 3D pole array for further performance optimization and control implementation [90]. Xia proposed a Halbach PM array to obtain a sinusoidal distribution of the magnetic field [91]. A high-performance orientation detection system was developed by Chen et al. [92] for improving the precision of orientation measurements. This was achieved by a passive spherical joint that connects the rotor with the base. Trajectory-tracking control algorithms can be found in the literature [93,94].

In a recent attempt to improve the performance of spherical motion generators, Li et al. designed a novel integrated spherical motion generator built on the basis of a spherical motor and a spherical parallel manipulator [95], as shown in Fig. 6. The new motion generator integrates an electromagnetic actuator with a 3RRR spherical parallel manipulator, thus leading to a more compact and light-weight structure, with the advantages of zero backlash, high stiffness and low inertia.

6. Recent developments of SMG for novel applications

Recent developments of spherical motion generation are noticeable. They have been developed for novel applications, particularly exoskeletons. These are found in one of the focus areas that have attracted most attention in this century [96–100]. Exoskeletons are robotic systems mounted on the human body for motion assistance, power augmentation, regaining motor functions, etc. In the human body, the wrist, the shoulder and the hip joints are all quasi-spherical[5] motion generators. These are critically important and challenging to design and work as joints at shoulder, wrist, hip, or ankle, while complying with the human anatomical structure. Exoskeleton joints have to be designed such that they surround the organic joint, the shoulder, for example, while pairing with the corresponding motion. This requires that a spherical joint mechanism

[4] See footnote [1].

[5] The axes of rotation of these natural mechanisms are fairly close to intersecting.

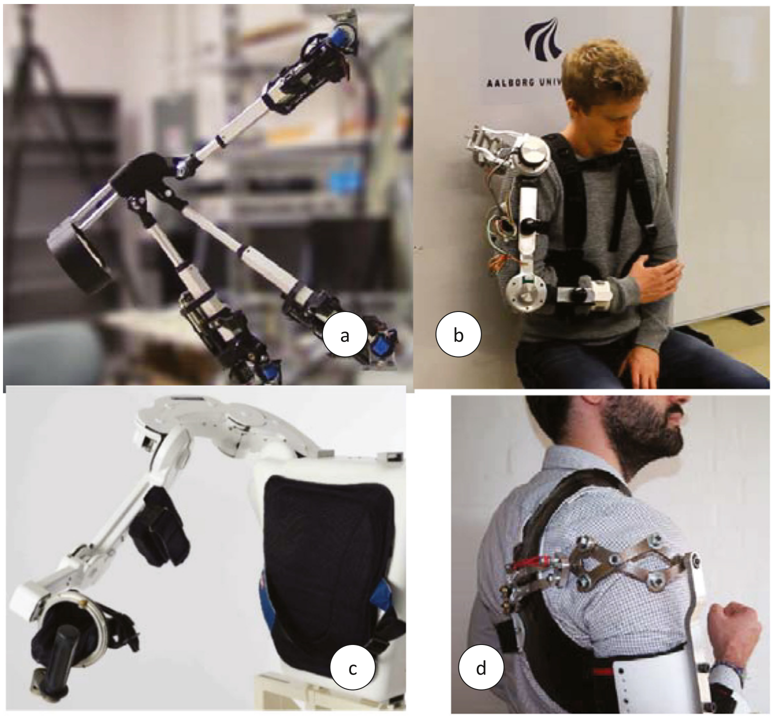


Fig. 7. Shoulder exoskeletons, (a) a five-dof shoulder exoskeleton containing 3-dof spherical parallel mechanism [102], (b) an upper-body exoskeleton, in which the shoulder mechanism was designed with double parallelograms [103], (c) ALEx exoskeleton [104], (d) a shoulder exoskeleton built with a spherical scissor mechanism [105].

for an exoskeleton be designed with a remote center of rotation, located in the space occupied by bones and muscles. The center has to coincide with the anatomical center of its natural counterpart in the human body to avoid discomfort [101]. Besides, there are also constraints on the size and weight for portable systems.

Many new joint designs differing from industrial wrist mechanisms have been developed, for example, a human–machine interface wrist with one single internal rotation center, which is efficient in terms of performance, size, and kinematic-interference avoidance, was proposed by Lee et al. [106]. It is intended to realize the three-dof rotational motion of the human wrist. The design of a 4R shoulder mechanism, as proposed by Lo et al. [107], uses a redundant revolute joint.

A shoulder mechanism designed using a double-parallelogram mechanism was proposed by Christensen and Bai [103]. The mechanism, shown in Fig. 7(b), has three dof of rotation and is able to produce singularity-free rotations in the anatomical shoulder-joint workspace. By utilizing double parallelograms, the mechanism can maintain a desirable structural stiffness for torque-and-force transmission, while keeping the mechanism compact and light. In a recent work by Castro et al. [105], a shoulder mechanism was designed by extending the planar scissor linkage to a spherical mechanism, thus yielding a compact solution comparable to a serial spherical mechanism, as shown in Fig. 7(d). The linkage has a small footprint, yet is able to achieve, singularity-free, throughout virtually the whole range of the human-arm motion.

A five degree-of-freedom low-inertia shoulder exoskeleton was reported by Hunt et al. [102], as shown in Fig. 7(a). The shoulder exoskeleton comprises a three-dof SPM and a two-dof passive slip interface, which is used to couple the user upper arm to the SPM. The slip interface can increase system mobility and prevent joint misalignment caused by the translational motion of the wearer's glenohumeral joint.

Fig. 7 (c) shows a six-dof mechanically compliant exoskeleton, called ALEx, for the human upper limb. Of its six dof, four are sensorized and actuated for shoulder abduction, rotation, flexion, and elbow flexion, while two dof are sensorized and passive for forearm prono-supination and wrist flexion. The shoulder rotation is implemented by means of a remote center of rotation [104].

Besides exoskeletons, spherical motion generators are increasingly applied in rehabilitation robots. A three-dof parallel manipulator was designed by Patene and Cappa for the rehabilitation and evaluation of balance performance [3,108]. Malosio et al. developed a spherical parallel robot for ankle rehabilitation [109]. The design of an ankle rehabilitation robot was reported by Du et al. [110], while a spherical parallel robot for shoulder rehabilitation was developed by Vaida et al. [108]. Robotic rehabilitation for post-stroke patients or other neural-impaired patients is an on-growing field of research that can provide personalized care with maximum therapeutic effects; it calls for innovative robotic systems.

In addition to robotic exoskeletons and rehabilitation robots, other new developments of spherical motion generators can be cited. In the work reported by Wu and Bai, a 3RRR SPM with co-axial actuators was redesigned with reconfigurability [111]. By means of a simple four-bar linkage, the SPM is able to change virtually the dimensions of its driving links. The new design allows the SPM reconfigurability for investigation of the influence of the link dimensions on the kinematics and dynamics performance. Moreover, the new design can be used directly for applications such as flight simulation or ankle-joint rehabilitation. A three-dof dexterous robotic wrist for micromanipulation was reported by Hammond et al. [112]. The design combines the mechanical stiffness and precision of conventional parallel manipulators with the large workspace and dexterous motion of serial manipulators to improve the performance, thus achieving a manipulator design of relatively high precision. The maximum achievable motion resolution was recorded at 0.1°. A redundantly actuated PKM was proposed by Valašek et al. for an application of telescope-mounting, in which redundancy is adopted to improve the dexterity [113]. Designs of leg and hand mechanisms based on SPMs can be found in [114,115].

7. Discussion on future research issues

While research has been conducted in many directions of spherical parallel manipulators, with great progress made, there are some outstanding issues that call for further study.

- *Kinematic analysis*
  One issue is workspace assessment. Li et al. [8] showed graphically the workspace of a pointing device, depicted in the form of 3D surfaces. Note that a pointing device has two degrees of freedom. On the other hand, most spherical motion generators have three degrees of freedom. For three-dof spherical motion generators, the workspace is a 3D volume. Up to date, an intuitive method that can illustrate and assess the workspace of a spherical parallel manipulator is lacking. A geometric method capable of showing the whole image of the workspace is desirable.
  In addition to workspace, other kinematic performance indices must be considered too. One of them is dexterity, originally defined for industrial manipulators [116] to assess their capability of achieving any orientation within their workspace. While other definitions of dexterity, varying considerably, have been proposed [117–119], they were intended for manipulators and grippers/hands, but not for spherical motion generators. It has to be noted that, for spherical motion generators, positioning is not an issue; only orientation is. The definition of dexterity must thus be revised to reflect the motion capability at stake.
  Other indices, including e.g., the global conditioning index, should also be reconsidered for their proper use, even if they have been adopted in SPM analysis and design optimization [26,62,65,120]. For serial manipulators, reach and dexterity are major concerns of the kinematic performance in many applications [121]. However, for spherical motion generators, the motion capability is critical. New performance indices are needed for SPMs with regard to their special motion requirements [48,122].
- *Novel spherical mechanisms and actuators*
  As reviewed in this paper, the applications of spherical motion generators in exoskeletons and several other kinds of robots call for novel designs to meet the new challenges in these systems. This can be achieved by both a systematic methodology of type synthesis [19] and innovative mechanism designs.
  Novel mechanisms can be designed by juxtaposing SPMs with additional degrees of freedom. A SPM with four collinear actuators was reported by Leguay-Durand and Reboulet [15], which removed singularities, thereby improving dexterity. Novel mechanisms can also be developed in the form of hybrid spherical motion generators. Two ways of constructing a hybrid generator are possible, namely, by combining either parallel and serial mechanisms [112] or mechanisms/serial manipulators and spherical actuators [95,123].
- *Sensing of the orientation*
  This problem is a part of the general problem of *rigid-body pose estimation*. In the presence of one or several turning shafts in a SMG, encoders can be utilized to measure rotations of shafts and further calculate the orientation of interest [89,92,124]. However, in systems on which one cannot mount rotational encoders due to a lack of turning shafts, orientation sensing becomes challenging. An example of such applications is *rendez-vous operations*, where one rigid object, e.g., a spacecraft, is to meet a certain landmark of the *International Space Station (ISS)*, with the purpose, e.g., of delivering supplies to the crew on board the ISS. In this case one specific point of the former is to coincide with another given point of the latter. Moreover, the spacecraft is to "land" on the ISS at a prescribed orientation for proper docking. Point-relative position is simple to sense, for example, using proximity sensors. Attitude "proximity" is more challenging, in fact, to even define it. However, this can be determined by means of sensing the proximity of a constellation of points on spacecraft and ISS. Sensors used to detect point-position have been developed especially for aerospace applications [125]. By far the most preferred means of sensing orientation are based on visual systems. Here, binocular cameras are the most suitable, as they provide, in one single measurement, all three Cartesian coordinates of one point of one body in a frame attached to a second body. An example of such a system was reported recently [126]. When monocular cameras are used, then at least two measurements from different viewpoints are needed to determine the relative orientation of two points [127,128].

8. Conclusions

The authors provided an extensive review of the research and development issues of spherical motion generators, focusing on spherical parallel manipulators and spherical motors. The kinematic solutions to both the forward and the inverse problems, performance analysis and evaluation, and design optimization, among others, were reviewed. The review paid special attention to the recent developments of spherical joints for exoskeletons and other emerging applications. New research issues were identified and discussed.

Spherical motion appears extensively in robotic systems and their applications. R&D work on spherical motion generators is essential for the performance analysis and design of novel systems to meet the new challenges posed by emerging applications. As reviewed in the paper, the study of spherical-motion generation spans large areas of research, with many topics covered. Novel parallel manipulators and actuators have been conceived towards their applications in solving engineering problems. Future research issues were highlighted in this paper. These issues, along with others yet to come, call for a sustained and increasing effort to advance the state-of-the-art of spherical motion generators.

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