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Feasible Human-Spine Motion Simulators Based on Parallel Manipulators

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1. Introduction

In biological kinematics, motion of a spine is realized by a number of functional spinal units (FSU), as shown in Fig.1 (spineuniverse.com). Each FSU consists of two adjacent vertebrae and physiological organization joining FSUs end-to-end (Hou, 2005). Owing to the spine, vertebrates have more flexible torsos than others. To understand, simulate and utilize the motion of vertebrate's torso, international researchers have made many bio-vertebrate robots such as robotic dog (bostondynamics.com), fish (robotic-fish.net), snake (Hirose; nasa.gov; ri.cmu.edu; snakerobots.com), rabbit (jsk.t.u-tokyo.ac.jp), lizard (birg.epfl.ch) and humanoid robot (kawada.co.jp; sony.net; world.honda.com; Giuseppe et al., 2003).

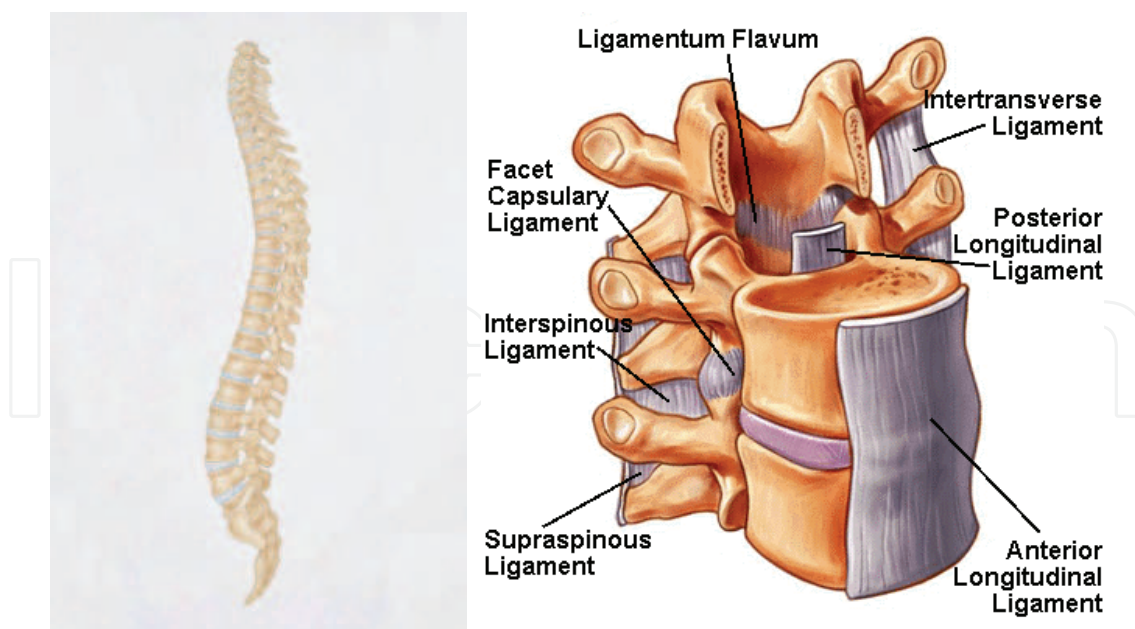


Fig. 1. A human-spine and FSU physiological organization

Torsos of some bio-vertebrate robots adopt torsos without bio-spine structure. As the most advanced quadruped robot on Earth, BigDog (bostondynamics.com) adopted rigid torso which result in the failure to realize the motion between shoulder and waist.

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To improve flexibility, some bio-vertebrate robots adopt bio-spine torso, which means a number of functional kinematic units (FKU, working as FSU) joined end-to-end through joining structure. Similar with the spine for vertebrates, the bio-spine torso enable maneuverability of bio-vertebrate robots. High maneuverability qualifies robotic fishes for the oceanographical observation, the leak detection on pipelines, the search for mines and the underwater archaeological exploration (robotic-fish.net). It also makes robotic snake be competent for search-and-rescue mission (ri.cmu.edu), exploring and building in space (nasa.gov) and moving both in water and on ground (Hirose).

Humanoid robots, as a special class of bio-vertebrate robots, have much wider applications than others. Researchers believe humanoid robots may be adopted in entertainment, cooperative works, maintenance and security task (Kazuo, 2003). Torsos of these robots are carried out in different ways (kawada.co.jp; sony.net; world.honda.com; Giuseppe, Hun-ok et al., 2003). ASIMO will realize 3-DoF for head and 1 for torso in next generation (world.honda.com); SDR-4X II realized 4-DoF for neck and 2 for torso (body) (sony.net); HRP-2 realized 2-DoF for head and 1 for torso (body) (kawada.co.jp); WABIAN-RV realized 4-DoF for neck and 3 for torso (Trunk) (Giuseppe, Hun-ok et al., 2003). From a medical point of view, vertebrae of human being are joined by intervertebral disc, ligaments and etc. Translation for one end of a spine to another along the axis of spine is mainly realized by bending, stretching and compressing ligaments and intervertebral discs. The range of such a translation is so small that can be ignored. Therefore, one end of spine for human has 3 rotational and 2 independent translational DoFs (3R2T) relative to another instead of theoretical 6 DoFs.

To the best of our knowledge, most existing humanoid robots accomplish motion of torso through a serial mechanism. For a serial manipulator, the motor closed to the base has to bear the mass of the motors closed to the manipulating end. Consequently, the link closed to the base is much stronger than that closed to the manipulating end, which exhausts extra energy and slows down the reaction. Different with a serial manipulator, a parallel manipulator may assembled all motors on the base. Such a base-actuator structure will lighten links and consequently improve working speed. For example, **DELTA**, a famous successful parallel manipulator, "*the use of base-mounted actuators and low-mass links allows the mobile platform to achieve accelerations of up to 50 G in experimental environments and 12 G in industrial applications*" (parallelemic.org). Moreover, kinematic performance of a spine for vertebrate is closed to isotropy. However, a parallel manipulator does not necessarily have isotropic kinematical performance as a serial manipulator. To achieve the kinematical performance closed to isotropy, a parallel manipulator should be fully-symmetrical (FSPM) (Mohamed, 1984), which means identical limbs, symmetrical assembly condition and actuating mode.

To simulating the motion of a human spine, the manipulator should satisfy not only on mobility property, reachable workspace and isotropic kinematical performance, but static and dynamic performance. A spine of human usually can work under two different modes: active mode and passive mode. Under active mode, muscles and ligaments control the motion of the spine following the person's will. Under passive mode, the spine passively moves under the outside load. To satisfy both modes, the manipulators had better to have less prismatic or cylindrical pairs considering that passive translation may result in extra resistance caused by non-coaxial and low working speed especially for ball screw, which will lead poor mechanics performance.

Considering the requirement mentioned above, a 3R2T 5-DoF base-actuator FSPM without prismatic or cylindrical pairs is necessary for a simple and efficient spine motion simulator. In the currently study, three such manipulators, 5-RRR(RR), 5-(RRR)RR and 5-(RRR)(RR) had been selected as the spine motion simulators. Respective kinematics properties are also illustrated and compared with each other. On this basis, a 5-RRR(RR) prototype is designed and manufactured as the human spine motion simulator prototype. Motion capacity between the prototype and different parts of human spine are compared. In the rear part of the literature, future work for further improve the simulation capacity of the prototype is planned.

2. Manipulator enumeration

Type synthesis of 3R2T FSPM had been a difficulty (Merlet, 2000) and hot topic until dozens of them are proposed (Jin et al., 2001; Fang & Tsai, 2002; Huang & Li, 2002; Kong & Gosselin, 2002; Giuseppe, Lim et al., 2003; Li et al., 2004). Comparing with the degree of concern for them in type synthesis, their application seems to be an inactive area.

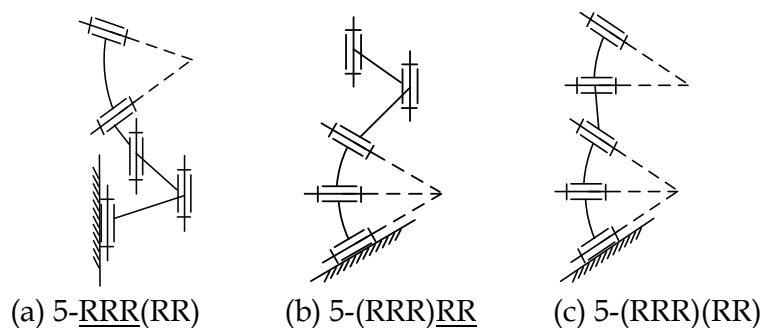


Fig. 2. Three FSPMs for spine-motion simulator

Among near twenty theoretical types of 3R2T FSPMs currently, there are only three manipulators without passive prismatic and cylindrical pairs, including 5-RRR(RR), 5-(RRR)RR, 5-(RRR)(RR) as shown in Fig.2, where "AB" denotes axes of pairs A and B are parallel, "(AB)" denotes axes of pairs A and B intersect at a common point.

2.1 5-RRR(RR)

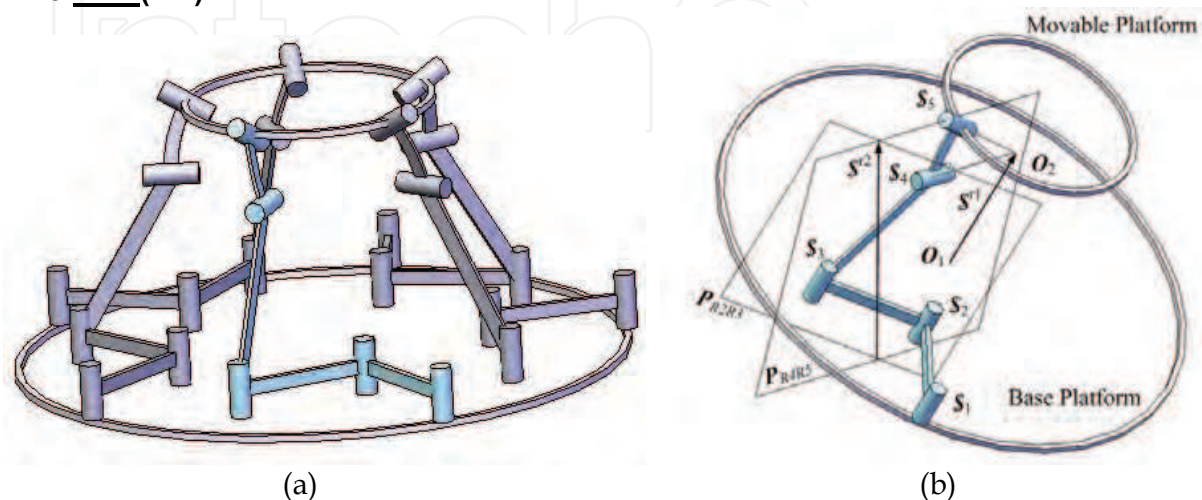


Fig. 3. 5-RRR(RR)

For a 5-RRR(RR) parallel manipulator shown in Fig. 3, the movable and base platforms are connected by five identical limbs each with five revolute joints. Axes of three joints adjacent to the base platform are perpendicular to the base; the other two intersect at point O_2 . The line passing through the origin O_1 and O_2 is perpendicular to the base platform. Let the x-axis be normal to axis of the first joint and z-axis point from O_1 to O_2 . In such a coordinate frame, the reciprocal screw (Ball, 1900; Hunt, 1978) of limb screw system is $\$^{r1} = [0,0,1; 0,0,0]$, whose axis is normal to the base, as shown in Fig. 3(b). The reciprocal screws of five limbs are the same. So the five constraints exerting on the movable platform form a common wrench with zero-pitch which constrains the translational freedom along the z-axis. So the movable platform has three rotational and two translational freedoms in a plane parallel to the base platform. As all actuators are locked, the screw system changes to be

$$\begin{aligned}\$2 &= [S_2; S_{02}] = [0,0,1; p_2, q_2, 0] \\ \$3 &= [S_3; S_{03}] = [0,0,1; p_3, q_3, 0] \\ \$4 &= [S_4; S_{04}] = [l_4, m_4, n_4; p_4, q_4, 0] \\ \$5 &= [S_5; S_{05}] = [l_5, m_5, n_5; p_5, q_5, 0]\end{aligned}\quad (1)$$

According to the screw theory (Ball, 1900; Hunt, 1978), it can be found that $\r1 and $\r2 are the reciprocal screws for the screw system expressed in Eq.(1) by inspection, shown in Fig. 3(b). The axis of $\r2 is the intersecting line of two planes P_{R2R3} and P_{R4R5} . P_{RiRj} denotes the plane determined by the axes of kinematic pairs R_i and R_j . The equation system for the axis of $\r2 is

$$\begin{aligned}N_1 \cdot [x-x_{R2}, y-y_{R2}, z-z_{R2}] &= 0 \\ N_2 \cdot [x-x_{o2}, y-y_{o2}, z-z_{o2}] &= 0\end{aligned}\quad (2)$$

where N_1 and N_2 denote the normal vectors of the plane P_{R2R3} ($N_1 \cdot S_2 = N_1 \cdot S_3 = 0$) and plane P_{R4R5} ($N_2 \cdot S_4 = N_2 \cdot S_5 = 0$), respectively. $[x_{o2}, y_{o2}, z_{o2}]$ and $[x_{R2}, y_{R2}, z_{R2}]$ are the coordinates of O_2 and the center point of the 2nd kinematic pair adjacent to the base, respectively.

In the general configuration, five $\r2 of five limbs are linear independent and every $\r2 is linear independent with the common constraint $\r1 . So there are six linear independent constraints exerting on the movable platform when the five actuators are locked. Therefore the selection of the base actuators is feasible and the manipulator is fully-symmetrical.

However, the manipulator will be singular if the configurations of all five limbs are identical as shown in Fig. 3(a). Under such a configuration, the five reciprocal screw $\r2 with zero-pitch of five limbs are distributed on a single hyperboloid of one sheet. Since the rank of screws on a hyperboloid of one sheet with one current is three, so the rank of constraints exerting on the movable platform is not six but four when all actuators are locked. That means the movable platform can still move after locking the actuators, and it is the second class of singularity in ref. (Gosselin & Angeles, 1990). To avoid such a singularity, the kinematic pairs which are not mounted on the base or movable platforms should be assembled with a little difference. For example, two limbs can be assembled in another current as shown in Fig. 4. This method is valid for currently existing 5-DoF FSPMs.

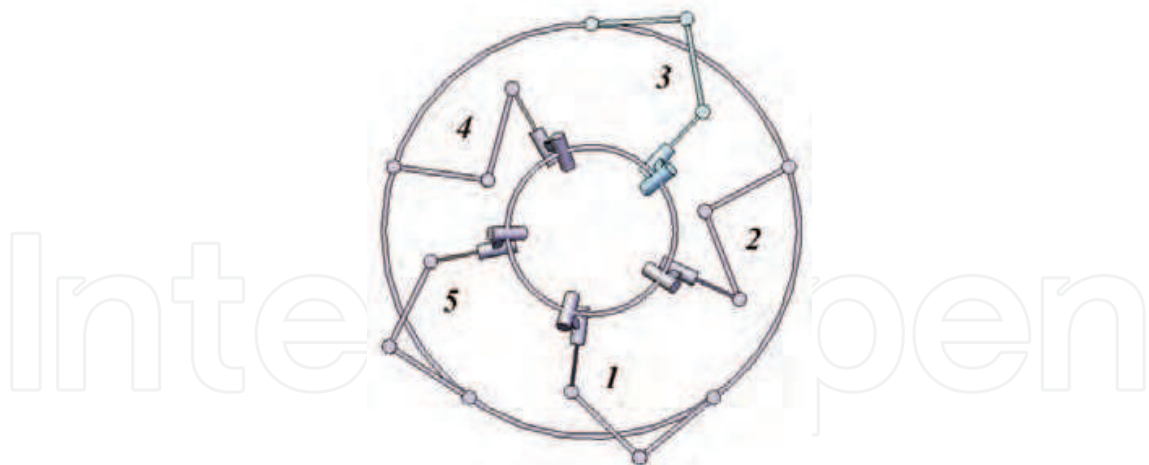


Fig. 4. Assembly condition for singularity avoidance

2.2 5-(RRR)RR

Although 5-(RRR)RR has a different structure with 5-RRR(RR), they have the similar constraint relationship, that is constraint screw of five limbs are the same. Hence, the mobility of 5-RRR(RR) is analyzed here in a simple way. In the similar coordinate frame in Fig.3(b), the reciprocal screw of five limb screw systems for 5-(RRR)RR are the same which form a common wrench $S^{r1} = [0,0,1; 0,0,0]$ constraining the translation along z-axis. The manipulator is the same with 5-RRR(RR) after locking all actuators, which means movable platform is fixed when all five actuators are locked at general configuration. Hence, base-actuator mode is valid for the manipulator 5-(RRR)RR.

2.3 5-(RRR)(RR)

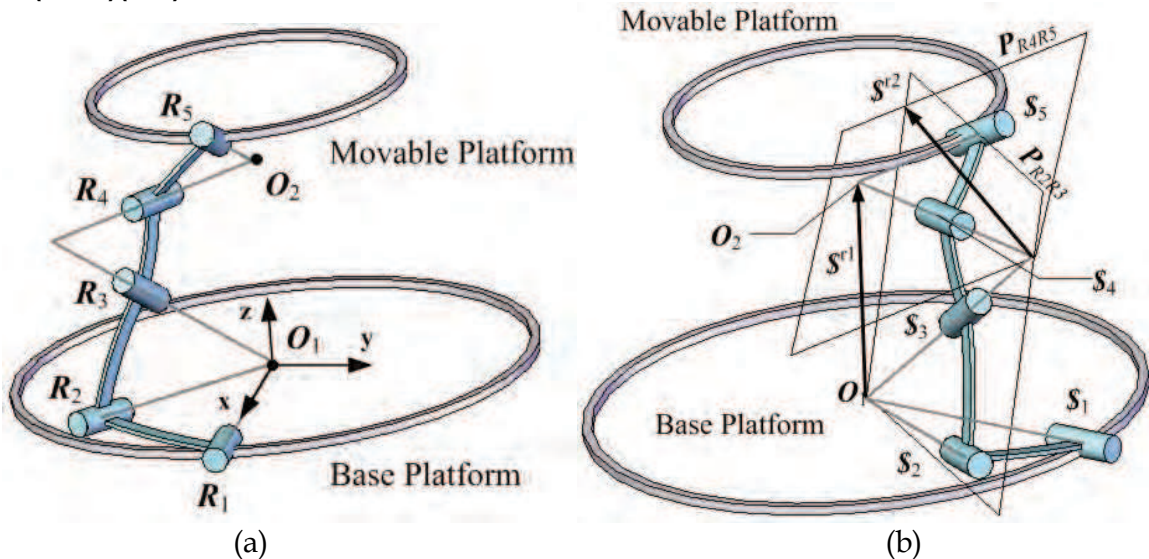


Fig. 5. 5-(RRR)(RR)

For a 5-(RRR)(RR) manipulator, the movable and base platforms are connected by five identical limbs each also with five revolute joints. Axes of three revolute joints adjacent to the base platform (R_1, R_2, R_3) intersect at a point O_1 . The other two (R_4, R_5) intersect at another point O_2 . Let O_1 be the origin, the x-axis be along the axis of R_1 and z-axis be

perpendicular to the base platform. In such a coordinate frame, the reciprocal screw of the screw system is a wrench with zero-pitch

$$\mathcal{S}^{r1} = [\mathbf{O}_2; 0,0,0] \quad (3)$$

whose axis passes through both \mathbf{O}_1 and \mathbf{O}_2 . The five reciprocal screws of five limbs are the same. So these constraints exerting on the movable platform form a common wrench with zero-pitch which constrains the translational freedom along a line passing through \mathbf{O}_1 and \mathbf{O}_2 . So the movable platform has three rotational and two translational freedoms. As all actuators are locked, the screw system changes to be

$$\begin{aligned} \mathcal{S}_2 &= [\mathbf{S}_2; \mathbf{S}_{02}] = [l_2, m_2, n_2; 0,0,0] \\ \mathcal{S}_3 &= [\mathbf{S}_3; \mathbf{S}_{03}] = [l_3, m_3, n_3; 0,0,0] \\ \mathcal{S}_4 &= [\mathbf{S}_4; \mathbf{S}_{04}] = [l_4, m_4, n_4; \mathbf{O}_2 \times \mathbf{S}_4] \\ \mathcal{S}_5 &= [\mathbf{S}_5; \mathbf{S}_{05}] = [l_5, m_5, n_5; \mathbf{O}_2 \times \mathbf{S}_5] \end{aligned} \quad (4)$$

The reciprocal screws for the screw system in Eq.(4) are \mathcal{S}^{r1} and \mathcal{S}^{r2} shown in Fig. 5(b). The axis of \mathcal{S}^{r2} is the intersection of two planes P_{R2R3} and P_{R4R5} . The parameter equation for the axis of \mathcal{S}^{r2} is

$$\begin{aligned} N_1 \cdot [x-x_{o1}, y-y_{o1}, z-z_{o1}] &= 0 \\ N_2 \cdot [x-x_{o2}, y-y_{o2}, z-z_{o2}] &= 0 \end{aligned} \quad (5)$$

where N_1 and N_2 denote the normal vector of the plane P_{R2R3} ($N_1 \cdot \mathbf{S}_2 = N_1 \cdot \mathbf{S}_3 = 0$) and plane P_{R4R5} ($N_2 \cdot \mathbf{S}_4 = N_2 \cdot \mathbf{S}_5 = 0$), respectively. Similar to the 5-RRR(RR), five \mathcal{S}^{r2} and \mathcal{S}^{r1} are six linear independent screws. So the selection of base actuators is feasible.

Note that, there is a obviously difference between the 5-(RRR)(RR) with the other two manipulators. For 5-RRR(RR) and 5-(RRR)RR, the constrained translation is always along the z-axis under different configurations. However, for the manipulator 5-(RRR)(RR), the direction of constrained translation is different under different configurations. As shown in Eq.(3), it always passes through \mathbf{O}_1 and \mathbf{O}_2 . The characteristic makes it be unique in currently existing 5-DoF FSPMs.

3. Prototype

A prototype is manufactured to verify the kinematic analysis and comparing the motion capacity of a human-spine and the prototype (Zhu, 2007). Considering that it is easy to guarantee parallelism than intersection at a common point in machining, 5-RRR(RR) is adopted as the manipulator prototype.

3.1 Structure

As mentioned in section 2.1, the axes for three joints adjacent to the base in one limb are parallel and the other two intersect at a common point. For the convenient to guarantee the machining accuracy, the prototype structure parameters are designed with special values. The axes of three joints adjacent to the base are designed to be perpendicular to the base

platform to guarantee the parallelism. The axis of R_4 is perpendicular to that of R_3 . Five arc links are manufactured through cutting a cylindrical ring averagely after drilling ten holes with indexing plate. One big and 15 small hole are drilled for lightening the movable platform. To avoid actuator singularity mentioned in section 2.1, limb are assembled as shown in the Fig. 4

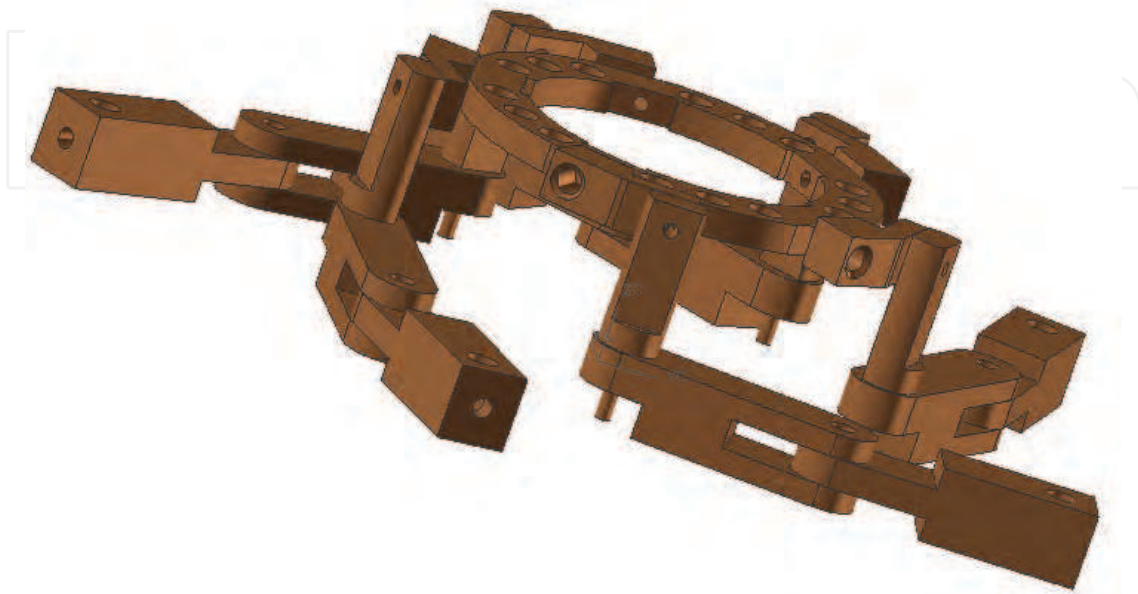


Fig. 6. 3-D model of the prototype

Diameters for movable and base platform are 109mm and 200mm. The length of both links connecting joints R_1 and R_2 , R_2 and R_3 are 44mm. To allow each arc-link rotate around axis of R_5 freely, the radian of the arc-link is 24 degrees. Five stepper motor controlled by a motion control card actuate five R_1 , respectively. The minimize step of the stepper motor is 0.018 degree under the cooperation with motion control card.

3.2 Reachable workspace

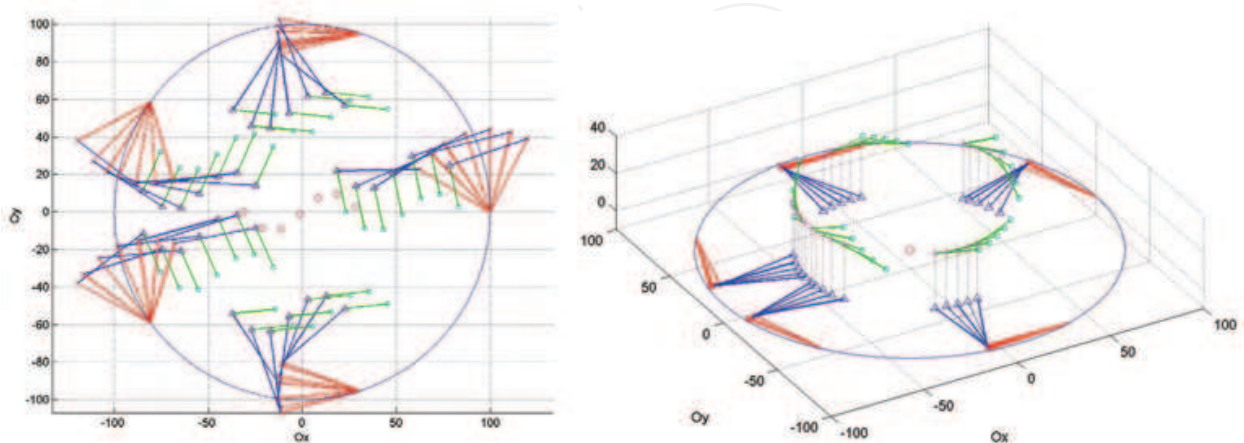


Fig. 7. Translation and rotation simulation of the prototype

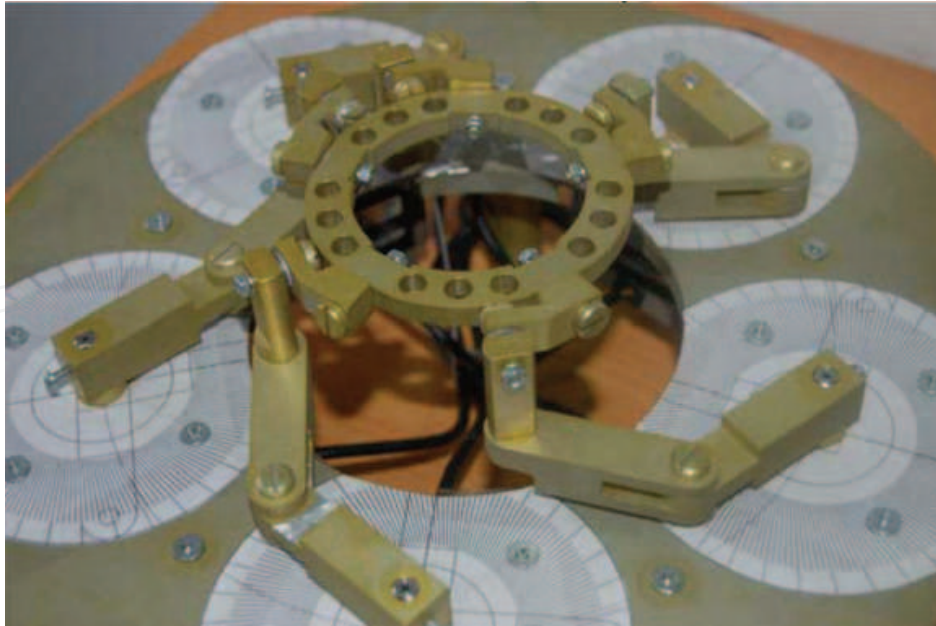


Fig. 8. Translation of prototype

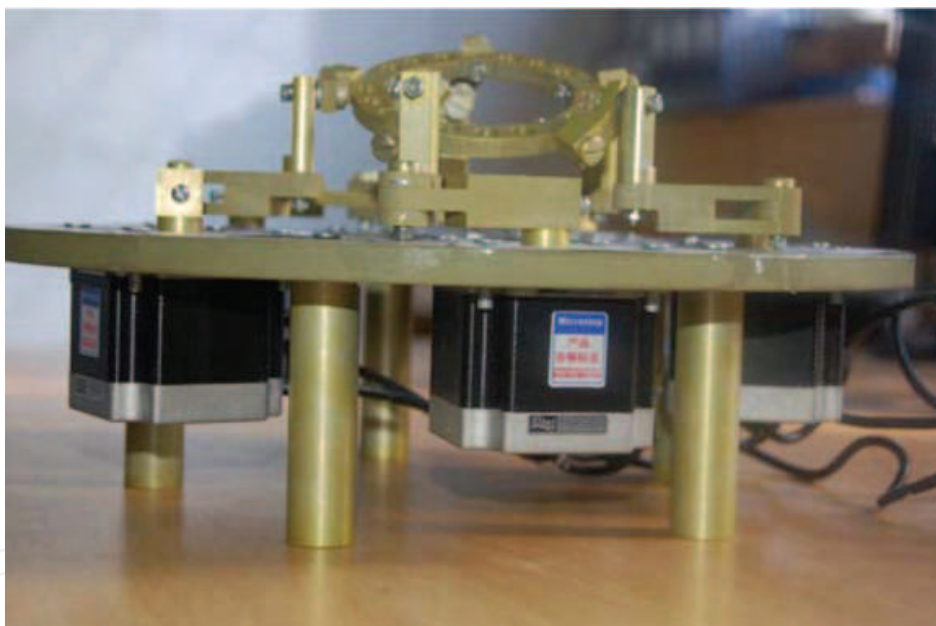


Fig.9. Rotation of prototype

According to the simulation, the reachable positions form a circle similar with a pentagon. The max translational distance is 89 mm, 44.5% of the diameter of the base. However, the max translation of the prototype is about 75mm because of interference. The rotation angles of the prototype around x-axis, y-axis and z-axis are 48, 48 and 66 degrees which is similar with the simulation. The motion of a spine is mainly realized by cervical spine, thoracic spine and lumbar spine. Considering rotation ability, cervical spine is the strongest (123, 61 and 77 degrees); the lumbar spine is the weakest (74, 29 and 9 degrees). Comparing with the three parts of human spine, the rotation ability of the prototype is similar to the thoracic spine, whose rotation angles are 76, 76 and 71 degrees, respectively.

5. Future work

Although mobility and kinematical performance closed to isotropy are realized through 5-DoF FSPM with base-actuator, there are still several aspects to be improved for further simulation capacity for the spine motion.

(a) Enlarge the reachable workspace. The reachable workspace of the prototype is smaller than that of human spine except the rotation around z-axis (yaw). Such a problem may be solved by rearranging the five R_4 . Immature hypotheses include, 1. arranging them in both sides of the movable ring platform, such as two inside and three outside; 2. Control link connecting R_3 and R_4 rotating within 180 degree instead of 360 degree through better trajectory plan to prevent link interference, which may enlarge the rotation angles around x-axis and y-axis to about 96 degree.

(b) Reaction time. The manipulator structure should be redesigned to ensure and improve the reaction time of the manipulator.

(c) Mechanics analysis. As mentioned in the literature, spine for human being may work under passive mode, in which passive force and torque should be calculated and evaluated under outside load. Hence, to simulate the bio-mechanics, static and dynamic behavior should be researched.

(d) Simulate with 5-(RRR)(RR) to make use of its unique characteristic.

6. Conclusion

Considering the characteristics of a human spine including nearly isotropic kinematical performance, fast speed, available under both active and passive modes and reachable workspace, three 3R2T 5-DoF fully-symmetrical parallel manipulators with base-actuator, including 5-RRR(RR), 5-(RRR)RR, 5-(RRR)(RR) are adopted as feasible human spine motion simulators. To decrease machining difficulty and guarantee the machining precision, 5-RRR(RR) is designed and manufactured as the prototype of spine motion simulator. After comparing reachable workspace of the prototype and that of human spine, the future work are planned for further improving simulation capacity of the prototype.

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In recent years, parallel kinematics mechanisms have attracted a lot of attention from the academic and industrial communities due to potential applications not only as robot manipulators but also as machine tools. Generally, the criteria used to compare the performance of traditional serial robots and parallel robots are the workspace, the ratio between the payload and the robot mass, accuracy, and dynamic behaviour. In addition to the reduced coupling effect between joints, parallel robots bring the benefits of much higher payload-robot mass ratios, superior accuracy and greater stiffness; qualities which lead to better dynamic performance. The main drawback with parallel robots is the relatively small workspace. A great deal of research on parallel robots has been carried out worldwide, and a large number of parallel mechanism systems have been built for various applications, such as remote handling, machine tools, medical robots, simulators, micro-robots, and humanoid robots. This book opens a window to exceptional research and development work on parallel mechanisms contributed by authors from around the world. Through this window the reader can get a good view of current parallel robot research and applications.

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