

Active Manipulator

FIELD OF INVENTION

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The invention relates broadly to an active manipulator, a passive rotational joint, and an active prismatic joint.

BACKGROUND

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Active manipulators provide fine orientation movements for high-precision manipulation. High precision manipulation has application in a large number of technologies such as in imprinting operations. Other examples include optics or laser-interferometer positioning in metrology systems, micro-scale handling and packaging processes, and nano-scale manipulation in robotic-assisted surgical devices or high-precision haptic devices etc.

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For example, in the field of nanoimprint lithography, conventional optical lithography runs into technical limits when used to produce transistors and resistors of sizes below 45 nm due to the wavelength limitation and diffraction effects of the photons. As such, Step-and-Flash Imprint Lithography (SFIL) or Ultra-Violet nanoimprint lithography has recently become a potential solution to replace conventional optical lithography. Unlike conventional nanoimprint lithography, SFIL is a room-temperature and low pressure process that relies on chemical and mechanical steps to transfer high resolution patterns from the templates (or molds) onto the substrates. With a liquid etch barrier, SFIL can eliminate the high temperatures and imprinting forces, which cause major technical issues in accurate overlaying of multiple layers. Consequently, it is the only nanoimprint lithography process that has successfully demonstrated the multi-layer-interconnections fabrications.

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In a SFIL system, a fine-orientation stage is usually driven by three high-resolution Piezoelectric (PZT) actuators to achieve active orientation motions about the x-axis, θ_x , and the y-axis, θ_y , and an active translational motion along the z-axis. PZT

actuators are solid-state transducers that are usually formed by naturally-occurring crystals such as quartz, tourmaline and sodium potassium tartrate etc. When such a crystal is exposed to an electric field, it experiences an elastic strain, which causes its length to increase or decrease according to the field polarity. As the elementary cells of the crystal material are strongly bonded, the elastic strain (physical changes) is usually very small. For example, a PZT actuator with a length of 100mm only produces a maximum displacement of 80 μ m (800V input). Based on this ratio, a PZT actuator with an estimated length of 5m only offers a displacement that is well under 5mm. Due to such physical constraints, the PZT actuators are usually employed in applications that require a few hundred micrometers displacement or less. With the PZT actuators limited to a few hundred micrometers, an additional Z-actuator must achieve micrometer resolutions, which is realized by a stepper motor and a micro-resolution linear ball-screw.

Therefore, there exists a need to provide an active manipulator to address one or more of the problems mentioned above.

SUMMARY

In accordance with a first aspect of the present invention, there is provided a manipulator comprising: a mobile platform; a base platform; at least three active limbs coupled between the mobile platform and the base platform such that the mobile platform is moveable in at least one translational and two rotational directions under the control of the active limbs; each active limb comprising: an active prismatic joint moveable in said one translational direction; a passive rotational joint for accommodating rotational movement of the mobile platform in said two rotational directions; and wherein for each active limb, a first connection to one of the base and the mobile platforms is via the passive rotational joint, and a second connection to the other one of the base and mobile platforms is rigid.

The active prismatic joint may comprise a magnet structure mounted to the base platform; a moveable coil extending through a magnetic field of the magnet structure; a compliant structure coupled between the moveable coil and the base platform.

The magnet structure may be configured for providing two magnetic fields, and the moveable coil extends through each of the magnetic fields.

5 The compliant structure may comprise a pair of linear spring structures coupled between the base platform and respective opposing ends of the moveable coil.

Each linear spring structure may comprise a double compound linear spring.

10 The double compound linear spring may comprise a set of beam-based flexure joints.

The passive rotational joint may comprise flexure joints defining two flexure axes extending substantially perpendicularly to each other across a body of the passive rotational joint.

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The passive rotational joint may further comprise a set of compliant compound linear springs for providing rotational movement about an axis parallel to the translational direction.

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The set of compliant compound linear springs may comprise a set of beam-based flexure joints.

The manipulator may further comprise a passive prismatic joint coupled between the active prismatic joint and the passive rotational joint.

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30 In accordance with a second aspect of the present invention, there is provided a passive rotational joint comprising flexure joints defining two flexure axes extending substantially perpendicularly to each other across a body of the passive rotational joint.

The passive rotational joint may further comprise a set of compliant compound linear springs for providing rotational movement about an axis parallel to the translational direction.

5 In accordance with a third aspect of the present invention, there is provided an active prismatic joint comprising a magnet structure mounted to a base platform; a movable coil extending through a magnetic field of the magnet structure; a compliant structure coupled between the moveable coil and the base platform.

10 The magnet structure may be configured for providing two magnetic fields, and the moveable coil extends through each of the magnetic fields.

The compliant structure may comprise a pair of linear spring structures coupled between the base platform and respective opposing ends of the moveable coil.

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Each linear spring structure may comprise a double compound linear spring.

The double compound linear spring may comprises a set of beam-based flexure joints.

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BRIEF DESCRIPTION OF THE DRAWINGS

25 Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

Figure 1 shows an example embodiment of a 3 PPS FPM.

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Figure 2 shows an example embodiment of each limb of the 3-DOF 3PPS FPM.

Figure 3 shows the active prismatic joint in the example embodiment.

Figure 4 shows the compliant spherical joint in the example embodiment.

Figure 5a shows a prototype of an example embodiment of the 3-DOF 3PU FPM.

Figure 5b shows an example embodiment of each limb of the 3-DOF 3PU FPM

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Figure 6 is a graph showing laser interferometer readings of the end-effector of the prototype at neutral position when the servo-control of each active compliant prismatic joint is activated.

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Figure 7 is a graph showing laser interferometer readings of the end-effector of the prototype when the prototype is manipulated to move from neutral position to 60 nm along the z-axis and back to neutral with an incremental step of 20 nm.

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Figure 8 shows a photoelectric autocollimator evaluating an orientation resolution of the prototype 500 of the example embodiment.

Figure 9 is a graph showing laser interferometer readings of the end effector a when the prototype is manipulated to move from neutral position to 2.5mm.

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Figures 10a and 10b show a 15 Kg-load placed on the prototype of the example embodiment as it is manipulated.

DETAILED DESCRIPTION

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It is to be noted that some elements in different embodiments of the present invention are the same and would therefore be similarly referenced with the same numeral.

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Embodiments of the present invention relate to a nano-alignment manipulator capable of large displacements and orientations with nanometric resolutions. An example embodiment of the manipulator is based on a 3-limbs prismatic-prismatic-spherical parallel kinematics configuration. Each limb is driven by a Lorentz-force actuating scheme that adopts a dual-magnet configuration to achieve large continuous thrust force with small input current and a compact-sized design.

Embodiments of the present invention seek to provide a θ_x - θ_y -Z manipulator of large workspaces with nanometric resolutions and large continuous output force. The embodiments of the present invention seek to provide a compliant manipulator based on the amalgamation of compliant bearings and an electromagnetic driving scheme. In the example embodiments, beam-based flexure joints are used as frictionless bearings to support the non-contact actuation of a Lorentz-force actuation. A Dual-Magnet (DM) configuration is employed in the embodiments of the present invention to enhance the strength of the magnetic field within an Electromagnetic Driving Module (EDM) so as to increase the current-force sensitivity and subsequently to achieve a larger force generation.

In the embodiments of the present invention, a 3-limb Prismatic-Prismatic-Spherical (3PPS) parallel-kinematics configuration is provided to realize the θ_x - θ_y -Z motion. One of the advantages of such embodiments using a parallel-kinematics configuration is that they can avoid the use of passive compliant revolute joints. This is because a passive compliant revolute joint, which typically targets for larger displacements, requires a thin slender design that is unsuitable for withstanding an imprinting force of 100N or more. In addition, such a slender designed flexure joint is sensitive to external disturbances, e.g., vibration etc, and possesses poor off-axis stiffness, which will affect the precision of the motion. The 3PPS parallel-kinematics configuration of embodiments of the present invention uses compliant prismatic joints, which can offer more deterministic or precise motion. Through symmetrical design and parallel configuration, embodiments of the present invention can possess higher off-axis stiffness to withstand the targeted imprinting force. Hence, embodiments of the present invention are constructed based on the 3PPS parallel-kinematics configuration, which can be classified as a three Degrees-Of-Freedom (DOF) 3PPS Flexure-Based Parallel-Kinematics Manipulator (FPM).

Figure 1 shows an example embodiment of a 3 PPS FPM 200. As illustrated in Figure 1, the 3-DOF 3PPS FPM 200 comprises of three identical partially-compliant limbs 202a, 202b, 202c attached to a base platform 212 using screws in the example embodiment and attached for supporting a mobile platform 210 using screws in the example embodiment. Figure 2 shows an example embodiment of each limb 202 of the

3-DOF 3PPS FPM 200. Each limb 202 comprises of an active compliant prismatic joint 204, a passive compliant prismatic joint 206 and a passive compliant spherical joint 208. As shown in Figure 2, each active compliant prismatic joint 204 carries the passive compliant prismatic joint 206 at its center of the actuating direction. A center 207 of a moving platform of the passive compliant prismatic joint 206 carries the passive compliant spherical joint 208.

Returning to Figure 1, each limb 202a-c is mounted on the base platform 212 with each limb 202a-c supporting respective edges 211a-c of the mobile platform 210. Each limb 202a-c is oriented such that they are each substantially perpendicular to the base platform 212 and mobile platform 210. More particularly, the respective active compliant prismatic joints 204 of each limb 202a-c are attached to the base platform 212, and the respective passive compliant spherical joints 208 of each limb 202a-c are attached to respective edges 211a-c of the mobile platform 210.

Figure 3 shows the active prismatic joint 204 in the example embodiment. As illustrated in Figure 3, to manipulate the 3-DOF 3PPS FPM 200, each active compliant prismatic joint 204 is driven by an EDM 302 with a DM configuration 304. The DM configuration or magnet structure 304 comprises of two pairs of parallel magnets, 305a and 305b. Each EDM 302 is constructed based on a moving air-core coil configuration 306 comprising an air-core coil 303 embedded within the DM configuration 304 such that the air-core coil 303 coils within respective gaps of each pair of parallel magnet 305a and 305b. As the air-core coil 303 extends through the magnetic field of the magnetic structure 304, passing current through the air-core coil 303 can result in translational movements of the air-core coil 303 in the z-dimension. The magnet structure 304 is rigidly coupled to a mounting bracket 310 of the active prismatic joint 204. As such, the Lorentz-force actuation results in the movement of the air-core coil 303, while the rigidly coupled magnet structure 304 remains in place. The passive prismatic joint 206 (Figure 2) is coupled onto the air-core coil 303 which allows for movements of the air-core coil 303 to be propagated towards the mobile platform 210 (Figure 1), via the passive prismatic joint 206 (Figure 2). The air-core coil 303 is wound onto a coil holder 307 having opposing ends 307a, b. The moving air-core coil configuration 306 and DM configuration 304 can allow high speed actuation, as a moving air-core coil is much lighter compared to a moving module, which comprises of the permanent magnets. In

addition, the DM configuration 304 can enhance the output force of each EDM. Hence, the additional force generated can advantageously also contribute to the actuating speed. At the same time, the DM configuration 304 can enhance the force generation without increasing the size and the amount of input current. The EDM 302 can offer a linear force-current relationship that allows the 3-DOF 3PPS FPM 200 (Figure 2) to perform a direct-force control during an imprinting process.

To retain the frictionless motion of the Lorentz-force actuation the active compliant prismatic joint 204 in the example embodiment further comprises compliant mechanisms, in the form of linear spring structures 308a, b. These linear spring structures 308a, b are coupled between the base platform 212 (Figure 1), via a mounting bracket 310, and respective opposing ends 307a, b of the coil holder 307. With the coils 303a wound onto the coil holder 307, the opposing ends 307a, b are exposed to allow the coils to be coupled to the linear spring structures 308a, b, via the opposing ends 307a, b. Both opposing ends 307a, 308b are coupled to the two linear spring structures 308a, b on each side of the EDM 302.

The opposing ends 307a, b of the air-core coil 303 are connected to the movable frames 312 of the linear spring structures 308a, b. When assembled, the movable frames 312 support the passive compliant prismatic joint 206 (Figure 2), more particular the respective legs 205a, b (Figure 2). The movable frames 312 are connected to the respective legs 205a, b (Figure 2) of the passive compliant prismatic joint 206 (Figure 2), using screws.

A rigid frame 314 is connected to the bracket 310 and hence the base platform 212 (Figure 1). For achieving nanometric resolutions over a few millimetres of travel of the air-core coil 303 with respect to the rigid base platform 212 (Figure 1), each compliant mechanism 308a, b comprises a double compound linear spring 311 with beam-based flexure joints 309. As illustrated in Figure 3, the EDM 302 is embedded within a pair of symmetrical double compound linear spring compliant mechanism 308a, 308b to form the complete active compliant prismatic joint 204.

In θ_x - θ_y -Z FPMs of the prior art, an elementary rod flexure joint has been a popular approach in realizing a conventional spherical joint motion, for example, in [6]

(K. M. Lee and S. Arjunan, A three-degree-of-freedom micromotion in-parallel actuated manipulator," in *IEEE International Conference on Robotics and Automation*, (Sacramento, California, USA), pp. 634{641, October 1991}) and in [9] (S. Q. Lee and D. G. Gweon, A new 3-dof z-tilts micropositioning system using electromagnetic actuators and air bearings," *Precision Engineering*, vol. 24, pp. 24{31, 2000}). However, an elementary rod flexure joint runs into its elastic deformation limit when larger deflections are required. In embodiments of the present invention, a compliant spherical joint is provided to address the limitations of the conventional elementary rod flexure joint. Figure 4 illustrates the compliant spherical joint 208 in the example embodiment. This compliant spherical joint 208 comprises of a compliant universal joint 402, which provides rotation motions about the x-axis, θ_x , and the y-axis, θ_y , independently, and a set of compliant compound linear springs 404 to provide a rotation motion about the z-axis, θ_z .

In the example embodiment, the compliant universal joint 402 is substantially of a hollow, cylindrical shape and divided into three portions 403a-c. As shown in Figure 4, portion 403a comprises two surfaces facing the portion 403b, inclined to the x-y plane and converging into a flexure joint 405a. The portion 403b provides a corresponding opening 407a around the flexure joint 405a, such that the portion 403a is coupled to the portion 403b via the flexure joint 405a. Similarly, portion 403c comprises two surfaces facing the portion 403b, inclined to the x-y plane and converging into a flexure joint 405c. The portion 403b provides a corresponding opening 407c around the flexure joint 405c, such that the portion 403c is coupled to the portion 403b via the flexure joint 405c. In the example embodiment, for each of the flexure joints 405a, 405c, a corresponding flexure joint 408a, 408c on each diametrically opposite side of the hollow cylinder 403a-c is also provided. It will be appreciated by a person skilled in the art that each pair of flexure joints on diametrically opposite sides lie on an axis of rotation. For example, flexure joints 405a and 408a lie on an axis of rotation, θ_y (as shown in Figure 4), while flexure joints 405c and 408c lie on an axis of rotation, θ_x (as shown in Figure 4). The two flexure axes, θ_x , θ_y , are substantially perpendicular to each other. Rotations about the x-axis, θ_x , (as shown in Figure 4) are therefore provided for by the flexure joints 405c, 408c, which join the portion 403b with the portion 403c. Similarly, rotations about the y-axis, θ_y , (as shown in Figure 4) are provided for by the flexure joints 405a, 408a, which join the portion 403b with the portion 403a.

In the example embodiment, compound linear spring design is used for providing rotation about the z-axis, θ_z , because it advantageously provides low displacement stiffness and can avoid parasitic motion. Sets of compliant compound linear springs 404
5 equally placed in a circular arrangement around the circumference of an enlarged hollow cylinder portion 410. The cylinder portion 410 comprises a top half 410a and a bottom half 410b, coupled to each other via the sets of compliant compound linear springs 404.

In another example embodiment, a θ_x - θ_y -Z FPM capable of achieving a targeted
10 large controllable workspace of $\pm 2.5^\circ \times \pm 2.5^\circ \times \pm 2.5$ mm is provided. Based on this workspace, the inventors have performed analysis which has indicated that the passive motions of each limb, i.e. the passive prismatic and spherical motions, can be realized by one universal joint. This is because the targeted workspace only requires very small passive prismatic and spherical motions that can be achieved by the compliance of the
15 beam-based flexure joints, which are used to form the universal joints. Consequently, a 3-limbs Prismatic-Universal (3PU) parallel-kinematics configuration may be employed to form a θ_x - θ_y -Z FPM with such a targeted workspace. Such a 3PU configuration offers a simplified and more compactly-sized FPM as compared to the 3PPS configuration 200 shown in Figure 2.

Figure 5a shows a prototype of an example embodiment of a 3-DOF 3PU FPM
20 500. As illustrated in Figure 5a, the 3-DOF 3PPS FPM 200 comprises of three identical partially-compliant limbs 502a, 502b, 502c attached to a base platform 512 and supporting a mobile platform 510. Figure 5b shows an example embodiment of each
25 limb 502 of the 3-DOF 3PPS FPM 500. Each limb 502 comprises of an active compliant prismatic joint 504, a platform 506 and a universal joint 508. As shown in Figure 5b, each active compliant prismatic joint 504 carries the platform 506 at its center of the actuating direction. A center 507 of the platform 506 carries the universal joint 508.

Returning to Figure 5a, each limb 502a-c is mounted on the base platform 512
30 with each limb 502a-c supporting respective edges 511a-c of the mobile platform 510. Each limb 502a-c is oriented such that they are each substantially perpendicular to the base platform 512 and mobile platform 510. More particularly, the respective active compliant prismatic joints 504 of each limb 502a-c are attached to the base platform

512, and the respective universal joints 508 of each limb 502a-c are attached to respective edges 511a-c of the mobile platform 510. The respective universal joints 508 are connected to the platform 506 via screws, while the platform 506 is further connected to the moving air-core coil of the active compliant prismatic joint 504 via screws.

A position control scheme was implemented on each active compliant prismatic joint to evaluate the open-loop performance of the prototype 500 shown in Figure 5. Figure 6 is a graph showing laser interferometer readings of the end-effector (i.e. the mobile platform 510) of the prototype 500 at neutral position when the servo-control of each active compliant prismatic joint is activated. It is observed that an average open-loop positioning resolution of ± 10 nm is registered with a maximum peak-to-peak resolution of ± 20 nm being traced occasionally.

Figure 7 is a graph showing laser interferometer readings of the end-effector of the prototype 500 when the prototype 500 is manipulated to move from neutral position to 60 nm along the z-axis and back to neutral with an incremental step of 20 nm. It is observed that the prototype 500 of the example embodiment is capable of a resolution of 20 nm.

Figure 8 shows a photoelectric autocollimator 802 (NIKON, model: Two-axes photoelectric autocollimator, resolution: $0.05''$ ($1/72000^\circ$)) evaluating an orientation resolution of the prototype 500 of the example embodiment. The prototype 500 is actively controlled to orientate the end-effector in an incremental step of $0.05''$ about the x-axis and the y-axis respectively while the autocollimator 802 measured the actual orientations.

Results tabulated in Tables 1 and 2 below indicate that the prototype 500 can achieve an orientation resolution of $0.05''$ about the x-axis and the y-axis respectively.

Desired orientation (")	Actual orientation (")
-0.05	-0.05
0.05	0.05
-0.10	-0.10
0.10	0.10
-0.15	-0.15
0.15	0.20
-0.20	-0.20
0.20	0.20
-0.25	-0.25
0.25	0.25
-0.30	-0.30
0.30	0.30

Table 1. List of the desired and actual fine orientations about the x-axis.

Desired orientation (")	Actual orientation (")
0.05	0.05
-0.05	-0.05
0.10	0.10
-0.10	-0.10
0.15	0.15
-0.15	-0.15
0.20	0.20
-0.20	-0.20
0.25	0.25
-0.25	-0.25
0.30	0.30
-0.30	-0.30

Table 2. List of the desired and actual fine orientations about the y-axis.

To evaluate the workspace of the prototype 500, a laser tracking robot (LEICA, model: Absolute Tracker, measuring volume: 18 m3, resolution: 60 μ m) was used and results are tabulated in Table 3. The results indicate that the prototype can achieve a large controllable workspace of at least $\pm 2.5^\circ \times \pm 2.5^\circ \times \pm 2.5$ mm.

Achieve by prototype	Positive	Negative
Position at the z-axis	2.514 mm	-2.500 mm
Orientation about the x-axis	2.981°	-2.868°
Orientation about the y-axis	2.578°	-2.556°

Table 3. List of the positions and orientations achieved by the prototype

The position control scheme was also used to move the end-effector of the prototype from 0 to 2.5 mm in the z-direction. Using a laser interferometer mounted above the end-effector, this large displacement motion was monitored and plotted as shown in Figure 9. The step response registered by the laser interferometer indicates that the end-effector moved from the neutral position to about 2.5 mm within 10msec before settling at 2.5 mm at approximately 100 msec. Based on this step response, the prototype demonstrates a fast travelling speed of 250 mm/sec.

Figures 10a and 10b show a 15 Kg-load placed on the prototype 500 of the example embodiment as it is manipulated. Based on preset open-loop command signals and displacement sequences implemented on each active compliant prismatic joint, the prototype was able to manoeuvre the 15 Kg-load within its maximum achievable orientations about the x- and y-axes of $\pm 2.5^\circ$. This operation indicates that the prototype can achieve more than 100 N of continuous output force with a force-current sensitivity of 160 N/Amp. Consequently, the prototype is capable of generating a continuous output force of at least 300 N of with 2 Amp of input current.

The example embodiments may be suitable for realizing the active co-planar nano-alignment between the template and the substrates, and for enhancing the imprinting process in the nanoimprint lithography processes. Further, the example embodiments may be applicable to any nano-scale process that requires nano-to-meso manipulations.

In the example embodiments, the components are comprised mainly of aluminum or aluminum based alloys. For example, the base platform, mobile platform, passive prismatic joints, passive spherical joints, universal joints, mounting frames, linear spring structures, opposing ends of the air-core coil, movable frames, rigid frames, and flexure joints are made of aluminum or aluminum based alloys. It will be appreciated by a person skilled in the art that other materials may be used to fabricate the components mentioned. For example, the compliant joints may be fabricated with titanium alloys, spring stainless-steels alloys, spring steels (or carbon-steels), copper-beryllium alloys, bronze alloys, or silicon-based materials. In addition, the EDM e.g. 302 in Figure 3, is made of iron while the magnets 305a, b (Figure 3) are permanent magnets in the example embodiments.

It will also be appreciated by a person skilled in the art that while the rigid connections between the various components are provided by screws in the example embodiments, other rigid connecting methods such as by welding, epoxy, etc. may also be applicable.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific

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embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. A manipulator comprising:
 - a mobile platform;
 - a base platform;
 - at least three active limbs coupled between the mobile platform and the base platform such that the mobile platform is moveable in at least one translational and two rotational directions under the control of the active limbs;
 - each active limb comprising:
 - an active prismatic joint moveable in said one translational direction;
 - a passive rotational joint for accommodating rotational movement of the mobile platform in said two rotational directions;
 - and wherein for each active limb, a first connection to one of the base and the mobile platforms is via the passive rotational joint, and a second connection to the other one of the base and mobile platforms is rigid.
2. The manipulator as claimed in claim 1, wherein the active prismatic joint comprises:
 - a magnet structure mounted to the base platform;
 - a movable coil extending through a magnetic field of the magnet structure;
 - a compliant structure coupled between the moveable coil and the base platform.
3. The manipulator as claimed in claim 2, wherein the magnet structure is configured for providing two magnetic fields, and the moveable coil extends through each of the magnetic fields.
4. The manipulator as claimed in claims 2 or 3, wherein the compliant structure comprises a pair of linear spring structures coupled between the base platform and respective opposing ends of the moveable coil.
5. The manipulator as claimed in claim 4, wherein each linear spring structure comprises a double compound linear spring.
6. The manipulator as claimed in claim 5, wherein the double compound linear spring comprises a set of beam-based flexure joints.

7. The manipulator as claimed in any one of the preceding claims, wherein the passive rotational joint comprises flexure joints defining two flexure axes extending substantially perpendicularly to each other across a body of the passive rotational joint.

8. The manipulator as claimed in claim 7, wherein the passive rotational joint further comprises a set of compliant compound linear springs for providing rotational movement about an axis parallel to the translational direction.

9. The manipulator as claimed in claim 8, wherein the set of compliant compound linear springs comprises a set of beam-based flexure joints.

10. The manipulator as claimed in any one of the preceding claims, further comprising a passive prismatic joint coupled between the active prismatic joint and the passive rotational joint.