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(54) Title: A METHOD AND A DEVICE FOR INCREASING STIFFNESS OF A CONNECTING HEAD OF A ROBOT WITH A WORKING TOOL

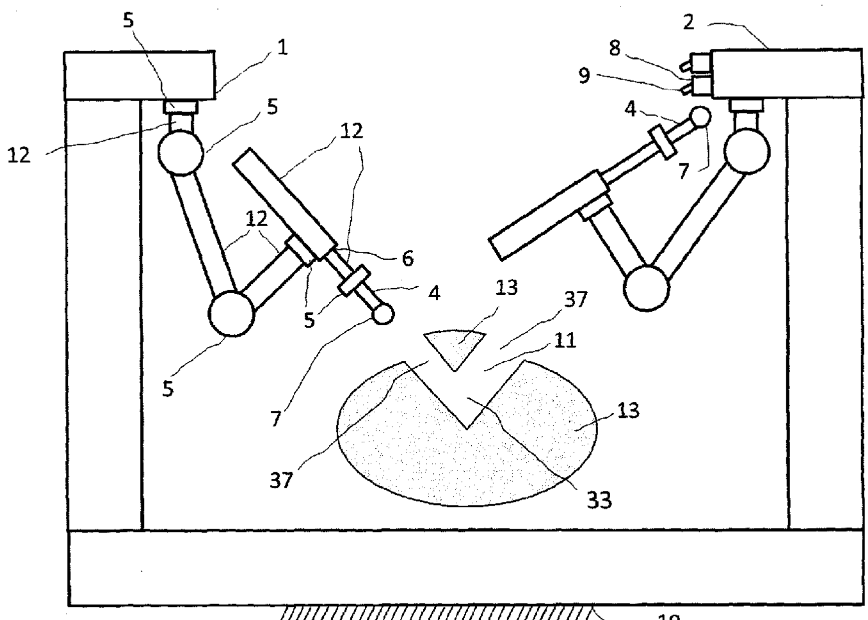

Fig. 1

(57) Abstract: The invention concerns a method for increasing stiffness of a connecting head of a robot with a working tool during its activity for carrying out a working operation in a target position in inaccessible or large spaces and lies in the fact that a connecting head with a working tool carried by an arm of a working robot and an arm of a supporting robot with a gripping head are moved into an inaccessible or large space, in the target position in the inaccessible or large space the robots get connected through the connecting head so that the gripping head carried by the supporting robot' s arm is connected to the connecting head carried by the working robot' s arm in the target position to carry out the operation by the working tool. A device for increasing stiffness of a connecting head of a robot with a working tool with at least two robots of a serial or parallel kinematic structure fitted with a gripping head for attaching to the connecting head, where the connecting head is fitted with at least two attachments for connecting to gripping heads of at least two robots particular arms of which are connected together through rotational joints and linear guides in the above mentioned way lies in that at least one of

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the robots is kinematically redundant, comprising more rotational joints or linear guides than six, or a handling arm of at least one of the robots is of a slender design or at least one of the robots is fitted either with a laser tracker or at least three laser reflectors.

A Method and a Device for Increasing Stiffness of a Connecting Head of a Robot with a Working Tool

Technical Field of the Invention

The invention concerns a method for increasing stiffness of a connecting head of a robot with a working tool during its activity in a target position in inaccessible spaces or large spaces for carrying out a working operation and a device for increasing stiffness of a connecting head of a robot with a working tool, with at least two robots of a serial or parallel kinematic structure fitted with a gripping head for connecting to a connecting head, where the connecting head is fitted with at least two attachments for attaching to a gripping head of at least two robots particular arms of which are connected together through rotational joints and linear guides, for carrying out a working operation.

State-of-the-art

Robots existing up to now, which operate in confined and limited spaces (generally inaccessible spaces), use arms with constricted cross-sections and often drive robot's joints through ropes with actuators placed on a frame. This results in decreasing stiffness and accuracy of such robots.
Solutions were proposed to increase stiffness of robots by connecting the robots together using a cooperative gripping head (PV 2012-474). Robots get connected together through a cooperative gripping head outside a working area and are connected in the place of the operation. However, such a solution requires a sizeable area. So this is not convenient for entering confined and limited spaces.
Another case is when robots have to carry out operations in large spaces. Robots for such operations have to be either big or mobile, so their stiffness is decreased. Achieving the required stiffness in such large spaces would demand the use of a large and heavy structure.
In order to reach into confined and limited spaces snake-like kinematically redundant robots are used, which have more joints and degrees of freedom than necessarily needed for reaching the required position. Adding more joints enables moving around in confined spaces but decreases stiffness and accuracy of the motion.
In order to increase stiffness robots with a parallel kinematic structure are used, however, this results in a need of an extensive workspace unsuitable for confined spaces.

The aim of this invention is a method and a device for increasing stiffness of a connecting head with a tool, thus increasing also the robot's accuracy for activities in confined and limited spaces or large spaces.

Subject Matter of the Invention

The subject matter of a method for increasing stiffness of a connecting head of a robot with a working tool during its activity in a target position in inaccessible or large spaces for carrying out a working operation lies in the fact that a connecting head with a working tool carried by an arm of a working robot and an arm of a supporting robot with a gripping head are moved into an inaccessible or large space, in the target position in the inaccessible or large space the robots get connected through the connecting head so that the gripping head carried by the supporting robot's arm is connected to the connecting head carried by the working robot's arm in the target position to carry out the operation by the working tool. The gripping head of the working robot with the connecting head with the working tool and/or the gripping head of the supporting robot is moved into an inaccessible area through a confined passageway. Before moving the connecting heads carried by arms of robots into a target position in a large space to carry out an operation by a working tool, the working and supporting robot has to be moved into a starting position. In the target position during the working operation the overdeterminated measurement of robots is performed, which lies in simultaneous measuring in actuators of all the connected robots for more accurate determination of their positions for feedback acting upon the actuators in order to reduce deviations of the connecting head from the required position, thus leading to the higher stiffness of the connecting head.
Or, during the working operation the additional measurement of robots is performed, which lies in simultaneous measuring of deformations of arms actuators and/or directly of the arm's motion on a rotational joint or a linear guide, possibly even of deformations of arms, of all the connected robots for more accurate determination of their positions for feedback acting upon the actuators in order to reduce deviations of the connecting head from the required position, thus leading to the higher stiffness of the connecting head. When re-positioning robots into the starting position in a large space for carrying out an operation by a working tool, the working robot measures its position by a laser tracker towards at least three laser reflectors located in the large space in order to facilitate navigation into the starting position and measures a position of the supporting robot in order to facilitate navigation of the supporting robot into the starting position, which lies in measuring the laser tracker position towards a position of at least three laser reflectors located on the supporting robot.

The subject matter of a device for increasing stiffness of a connecting head of a robot with a working tool, with at least two robots of a serial or parallel kinematic structure fitted with a gripping head for attaching to the connecting head, where the connecting head is fitted with at least two attachments for connecting to gripping heads of at least two robots particular arms of which are connected together through rotational joints and linear guides in a way mentioned above lies in that at least one of the robots is kinematically redundant, comprising more rotational joints or linear guides than six, or a handling arm of at least one of the robots is of a slender design or at least one of the robots is fitted either with a laser tracker or at least three laser reflectors. Attachments for attaching the connecting head to the gripping head of the robots, either on the side of the connecting head or on the side of the gripping head, are rotationally symmetrical or include rotational joints or linear guides without actuators. At least one of the robots is fitted with at least one additional sensor represented by an arm motion sensor on the rotational joint or linear guide, or an arm actuator deformation sensor or an arm deformation sensor. In some case, at least one robot is placed on a movable cart fitted with a device for attaching to a frame.

Overview of Figures in Drawings

The attached figures show schematic depictions of a device for increasing stiffness of a connecting head with a working tool for activities of robots in confined and limited spaces, where

Figs. 1 - 4 depict one of the basic embodiments,
Figs. 5 - 6 depict embodiments with a parallel kinematic structure of one of robots,
Fig. 7 depicts an embodiment with an additional robot,
Fig. 8 depicts a kinematic structure of the described robots with a marked Cartesian coordinate system,
Figs. 9 - 11 depict alternative embodiments of respective robots,
Figs. 12 - 15 depict an embodiment in large spaces,
Figs. 16 - 22 depict possible embodiments of actuators of robots,
Figs. 23 - 27 depict various embodiments of attachments for gripping and connecting heads,
Fig. 28 depicts an alternative arrangement of rotational joints in the robot structure,
Fig. 29 depicts another alternative arrangement of rotational joints in the robot structure and
Fig. 30 depicts an arrangement of robots and their navigation elements.

Examples of Embodiments of the Invention

Figs. 1 - 4 show an arrangement of a pair of robots for performing a working operation in confined or limited spaces, where Fig. 1 shows both of the robots in a certain starting position that in next Figures moves into the target position 33 in Fig. 4, where gripping heads 7 of both of the robots are attached to connecting head 8 carrying tool 9 for performing a working operation in target position 33.
Working robot 2 and supporting robot 1 of a serial kinematic structure are attached to frame 10; they consist of arms 12 interconnected through rotational or spherical joints 5 or linear guides 6 and are fitted with handling arms 4 with gripping heads 7 on their ends. On frame 10 there are connecting heads 8 located for connection to various tools 9 and to gripping head 7 of working as well as supporting robot 2. Robots 1 and 2 are equipped with actuators; actuators can also be in connecting head 8 for a motion of tool 9.

Fig. 1 shows working robot 2 in a position of gripping head 7 approaching one of connecting heads 8. Fig. 2 shows robot 2 with gripped connecting head 8 with tool 9 in a position before entering confined space 11 through passageway 37 among obstacles 13 inside the area. Fig. 3 shows robot 2 with gripped connecting head 8 with tool 9 moved into target position 33 in confined space 11, where tool 9 is to carry out the required operation. In order to achieve the stiffness needed for this operation supporting robot 1 has been moved into confined space 11 through passageway 37, as shown in Fig. 4. Passageways 37 can be limited, when only handling arm 4 with gripping head 7 or connecting head 8 with tool 9 is able to pass through. Supporting robot 1 with its gripping head 7 has reached connecting head 8 carried by working robot 2 and has connected its gripping head 7 to connecting head 8. Now connecting head 8 with tool 9 is carried by handling arms 4 of both robots 1 and 2. This is the first step to increase stiffness of connecting head 8 with tool 9 for the required operation. Actually, there is a sum of stiffness of handling arms 4 of both robots 1 and 2. Increasing stiffness of connecting head 8 with tool 9 leads to an increase in accuracy of its motion during the required operation. This is because of the fact that a deviation of the tool under the acting force is lower thanks to the higher stiffness.
The access of connecting head 8 into target position 33 inside confined space 11 among obstacles 13 is limited by a need to pass through passageways 37, some of which being with bigger limitations, enabling passing through of e.g. handling arm 4 of only one of robots 1 and 2. In order to improve a motion inside confined space 11, handling arms 4 connected to gripping head 7 do not comprise rotational joints 5 or linear guides 6, they are of a slender design with a slenderness ratio at least 1:5. Slenderness is the ratio of the length and the least radius of gyration of the cross section. A body is considered as slender when the ratio is at least 1:2, but it can be even many times higher.

Gripping head 7 of working robot 2 has been moved into confined space 11 through one passageway 37, while gripping head 7 of supporting robot 1 has been moved into confined space 11 through the second passageway 37. Some of passageways 37 can be highly limited passageways. In this particular case, passageways 37 were only used for the gripping head of one of robots 1 and 2. If possible, in order to increase stiffness of connecting head 8 in confined space 11, passageway 37 can be used for gripping heads 7 of both robots 1 and 2.

The second step to increase stiffness of connecting head 8 with tool 9 is an overdeterminated measurement thanks to the connected robots. In order to increase stiffness of connecting head 8 with tool 9 in confined space 11 the overdeterminated measurement of robots in target position 33 during the working operation can also be used. This overdeterminated measurement lies in simultaneous measuring in actuators of all the connected robots for more accurate determination of their positions for feedback acting upon the actuators of the robots in order to reduce deviations of connecting head 8 from the required position. Thus the higher stiffness of connecting head 8 can also be achieved because more accurate determination of the position results in lower deviations from the required position even under the acting forces.

Each robot is fitted with at least so many sensors how many actuators it has and it has so many actuators to be able to control all degrees of freedom, which means its movability, and to control the motion of gripping head 7. The number of degrees of freedom is a number of parameters needed to determine the robot's position unambiguously. After connecting robots 1 and 2 through connecting head 8, the movability given by the number of degrees of freedom gets reduced. Connected robots 1 and 2 have the movability equal to the number of degrees of freedom of each of the robots, however, they have two-fold number of actuators and position sensors. This represents the overdeterminated measurement of the position, which can be used both for a calibration of models of particular robots and then also of connected robots (the calibration means the determination of dimensions used for the models) and for an increase in accuracy of the position determination by redundant specification, for example by solving overdeterminated equations for relations of the connecting head position and the measured positions in joints and guides or by calculating an average of more solutions for the position of the connecting head and tool from redundant measurements of positions in joints and guides.

For increasing stiffness of connecting head 8 with tool 9 in confined space 11 additional sensors for measuring a deformation of the actual robot in comparison with its model as a solid robot can also be used. There is both a deformation of the motion transmission from the actuator to the robot arm motion and a deformation of arms and transmission system of the robot.

The stiffness and accuracy of positioning of robots is mostly caused by their pliability and subsequent deformation. The largest part of pliability of robots is in the transmission system between the actuator and the moving arm. This causes a difference between a motion of the actuator measured by an actuator sensor 15 and a motion of arms 12 of the robot. The transmission system consists of gear shaft 19 or rope 20 or a gearbox in the actuator and the pliability of the actuator motion transmission affects an arm rotation or displacement. This third step to an increase in stiffness of connecting head 8 with tool 9 is described in more details in Figs. 16-20.
The deformation is measured by sensors of the actual motion of robot arms.

The fourth step to an increase in stiffness of connecting head 8 with tool 9 is the use of additional sensors for measuring of both the deformation of transmission system and the deformation of robot arms. The deformation of the transmission system between an actuator and a moving arm or the deformation of robot arms is measured by additional sensors. A smaller part of pliability of robots is in the deformation of robot arms. A more detailed description is in Figs. 16-20.

Figs. 5 and 6 show robots having a parallel kinematic structure. A parallel kinematic structure means that a body (this is a handling arm here) of an end effector (gripping head 7 of the particular robot here) or another body in the structure is connected to more than two arms of a robot and is called platform 21.

In a robot with a serial kinematic structure the end effector is carried by one arm only and each body (arm) inside its structure is connected to two other arms. In a robot with a serial kinematic structure each rotational joint or linear guide is fitted with an actuator. As for a robot with a parallel kinematic structure: the stiffness is increased by bodies being carried by more arms and the weight can be reduced by incorporation of rotational joints or linear guides without actuators.

To be specific, Fig. 5 shows supporting robot 1 with a parallel kinematic structure, as handling arm 4 of supporting robot 1 is carried by two arms 12, the lower one of which is connected to handling arm 4 through rotational joint 5 and the upper one is connected to handling arm 4 through spherical joint 22. This increases stiffness of the end effector - gripping head 7. In addition, these joints – spherical joint 22 and rotational joint 5 along with preceding linear guide 6 are without actuators, thus reducing a weight of supporting robot 1. Moreover, supporting robot 1 in Fig. 5 has more actuators (eight) than needed degrees of freedom (six) and this redundancy of actuators results in increasing stiffness also with the aid of a special clearance control in order to increase accuracy of positioning and motion of gripping head 7 and, in the end, of tool 9.

Fig. 6 shows supporting robot 1 with a parallel kinematic structure, as platform 21 inside the structure of supporting robot 1 is carried by three arms 12 attached to platform 21 through spherical joints 22 and there is linear guide 6 with arm 12 carrying handling arm 4 with gripping head 7 coming out from platform 21. This increases stiffness both of platform 21 and of the end effector - gripping head 7. Further on, these spherical joints 22 and preceding rotational joints 5 are without actuators, thus resulting in a weight reduction of supporting robot 1.

There are many variants of robot designs with a parallel kinematic structure, Hexapod, Delta, Sliding Star, Hexasphere, etc. are well-known.

Fig. 7 illustrates that connecting head 8 with tool 9 can be carried by more robots, thus increasing stiffness of the connecting head with tool 9 even more. To be specific, aside from robots 1 and 2 from Figs. 1-4, Fig. 7 shows additional robot 3, which by its handling arm 4 through gripping head 7 grips connecting head 8 with tool 9. The increase in stiffness is still enhanced because effects of the connection through connecting head 8 are now summed up from three robots. Actually, a number of robots carrying connecting head 8 are not limited. Connected robots 1-3 can enter confined space 11 through various openings among obstacles 13 inside the area, as depicted in Fig. 7, however, they can enter together through smaller number of openings. So it is possible to have more robots with arms of smaller cross-sections that enter confined and limited spaces through more openings, where they get connected, thus achieving the increased stiffness perhaps even of one rigid arm of a large cross-section.

Fig. 8 shows in more details a kinematic structure of robots described in Figs. 1-7. Schemes of robots in Figs. 1-7 can be understood as topological arrangement of arms 12 connected through rotational joints 5, linear guides 6 or spherical joints 22 (not depicted here) leading from frame 10 to gripping head 7. However, these schemes also depict a more detailed description of a kinematic structure. Fig. 8 shows two schemes of supporting robot 1 from Figs. 1-7 side by side. On the left side there is a scheme as depicted in Figs. 1-7 and on the right side there is a spatial view on the same robot. Fig. 8 shows the Oxyz Cartesian coordinate system, where the O point and the x- and z-axes lie in the plane of Fig. 8 and the y-axis is perpendicular to the plane of Fig. 8. The scheme of robot 1 and 2 can represent a starting position of a robot lying in the Oxz plane (to be more accurate, the axes of the symmetry of its arms and joints and linear guides and gripping and connecting heads lie in the Oxz plane), from which the robot moves outside the Oxz plane by turning its rotational joints 5, spherical joints 22 or sliding in linear guides 6. In this interpretation the Figure can be read as that the marks used for rotational joints 5_1 are rotational joints with an axis of

rotation lying in the Oxz plane and the marks used for rotational joints $\underline{5_2}$ are rotational joints with an axis of rotation perpendicular to the Oxz plane, thus in the direction of the y-axis in the starting position. The spatial scheme depicts this interpretation of rotational joints $\underline{5_1}$ and $\underline{5_2}$.
This interpretation can be used in Figs. 1-7, 9, 12-14, 28.
However, the robots can be displaced or turned in various ways towards the plane in the Figures.

Figs. 9-11 show that kinematically redundant robots can be preferably used for operations in confined spaces 11. A kinematically redundant robot means a robot with more degrees of freedom than necessarily needed for achieving a random position and orientation of an end effector, which means 3 degrees of freedom in a plane and 6 degrees of freedom in a space. Redundant degrees of freedom are used for movability of a robot in confined spaces. This is especially advantageous for moving in confined spaces 11 through passageways 37 or even limited passageways. If any part of a robot that determines its movability requires a too large space for a motion of a following part of the robot, then by repeating some of rotational joints 5 or linear guides 6 the demanded handling (working) area can be limited.

In Fig. 9 only two rotational joints 5 are repeated. In supporting robot 1, after the first three rotational joints 5 from frame 10 there is joint 5 repeated congruently as the second and the third rotational joint 5. This is not important for a position and orientation of arm 12 with linear guide 6 but this position and orientation can be achieved in a smaller handling area for the first four rotational joints 5. Similarly at the end of the arm of robot 1 there is joint 5 repeated so that the orientation of handling arm 4 can be changed locally in confined space 11 and need not to be derived from the rotation of arm 12 with linear guide 6. This supporting robot 1 has seven rotational joints 5 and one linear guide 6 for the total six degrees of freedom of gripping head 7 in space. Redundancy of two rotational joints 5 allows performing a motion in a generally smaller handling area.

Fig. 10 shows a schematic depiction of an extensive application of redundant rotational joints 5 or linear guides 6 for a robot in an analogy with a movability of a snake.
Fig. 11 shows a schematic depiction of the use of a concept of a robot as depicted in Fig. 10 for getting through passageways 37, which can be limited, into confined space 11 of a non-convex type, where the orientation of individual arms 12 of the robot has to change the direction significantly.

Stiffness of connecting head 8 with tool 9 has also to be increased in large spaces.
A large space is an area that is larger than a working area of a typical robot and the robot cannot reach the whole area around. A robot for such a use should be big and heavy. Another

possibility is to move a smaller robot to a place in a large space, where a required operation has to be carried out. A smaller and movable robot has a lower stiffness, however, this can be improved by using more robots and their physical connection in a location of the required operation.

Figs. 12-14 show step by step a procedure of a method of increasing stiffness and accuracy of a robot for activities in large spaces 30. It is difficult to move big and rigid equipment into large spaces, so it is advantageous to move there more smaller devices that can get physically connected in the target area and perform a required operation with an increased stiffness and accuracy.

Fig. 12 shows a schematic depiction of a pair of robots 1 and 2 with a serial kinematic structure with handling arms 4 on the ends of which there are gripping heads 7. These robots 1 and 2 are placed on movable carts (platforms) 31 moving along frame 10. Their attachment to frame 10 subsequently improves equipment 32 for attachment to a floor (frame 10). An example, besides braking on the carts, can be a sucker. Robots 1 and 2 are attached to carts 31, they consist of arms 12 interconnected through rotational or spherical joints 5 or linear guides 6. Robots 1 and 2 are outside of target position 33 of the required operation in large space 30. Carts 31 with robots 1 and 2 are moved to starting position 38 of the required operation in large space 30. Starting position 38 in large space 30 is such a position from which a robot attached to frame 10 reaches target position 33, i.e. the working area of the robot in starting position 38 in large space 30 includes target position 33 where the required operation is to be carried out. Robot 2, as a working robot, has connecting heads 8 with various tools 9 placed on its cart 31.

In Fig. 13 carts 31 with robots 1 and 2 have been moved to starting position 38 in large space 30. To be more specific, both robots 1 and 2 have been moved into starting position 38 on frame 10. Both carts 31 are arrested and attached to frame 10 through fixing equipment 32. Starting position 38 in large space 30 for robot 1 or 2 is such a position from which a robot 1 and 2 attached to frame 10 reaches target position 33 of the required operation, i.e. the working area of robot 1 and 2 in starting position 38 in large space 30 includes target position 33. Working robot 2 grips by gripping head 7 an applicable connecting head 8 with tool 9 and moves it across large space 30 into target position 33, where the required operation is to be carried out by tool 9. In order to achieve the demanded stiffness for this operation gripping head 7 of supporting robot 1 moves also to target position 33 in large space 30.

Fig. 14 shows that supporting robot 1 with its gripping head 7 has reached connecting head 8 carried by working robot 2. Supporting robot 1 with its gripping head 7 has been connected to connecting head 8. Now connecting head 8 with tool 9 is carried by arms 4 of both robots 1 and 2. This is the first step to increase stiffness of tool 9 for the required operation.

Actually, there is a sum of stiffness of handling arms 4 of both robots 1 and 2. An increase in stiffness of tool 9 leads to an increase in accuracy of its motion during the required operation. This is given by the fact that a deviation of the tool under the acting force is lower due to the higher stiffness.

A method in Figs. 12-14 lies in that working robot 2 with gripping head 7 grips connecting head 8 with tool 9 and relocates it to target position 33 in large space 30 and supporting robot 1 relocates its gripping head 7 to this target position 33 from the other side. In target position 33 in large space 30, gripping heads 7 of robots 1 and 2 get connected through connecting head 8 and through this physical connection they achieve the increased stiffness and improved accuracy of positioning for carrying out the required operation by tool 9. This is important that the physical connection of the robots in order to achieve the increased stiffness and accuracy can be achieved this way in large space 30 without any big structures.

Fig. 15 shows a schematic depiction of large space 30 with target position 33 on object 39 for carrying out a required operation; the object being e.g. a big machine on which an operation, for example machining, is to be carried out. Carts 31 with robots 1 and 2 have been moved from the initial position to starting position 38 with a reach to target position 33.
Confined space 11 can also occur in target position 33 in large space 30. So even in large space 30, when robots 1 and 2 are in starting position 38 the stiffness of connecting head 8 with tool 9 can be increased when passing through passageway 37, or through a limited passageway, into target position 33 in confined space 11, as described in Figs. 1-4.

Fig. 16 shows a schematic depiction of actuator 14 and a rotation of arm 12. Actuator 14 is fitted with actuator sensor 15 and acts by torque M upon transmission shaft 19 fitted with additional sensor 16 for a motion of arm 12 by ϕ angle on the rotational joint (marked as 5 in Figs. 1-14). Sensor 16 for the arm motion can be supplemented by additional sensor 17 for a deformation of the arm actuator. The very arm 12 can be fitted with additional sensor 18 for the arm deformation. Typically actuator 14 is fitted only with sensor 15 for the actuator. In order to determine arm 12 motion more exactly, either additional sensor 16 of a motion of arm 12 or additional sensor 17 for a deformation of the arm actuator is used. A bigger part of a deviation of a motion of arm 12 from a deviation measured by actuator sensor 15 is a deformation of the actuator of arm 12 measured by additional sensors 16 and 17. Other part of the deformation is measured by additional sensor 18 for the arm deformation.

Fig. 17 shows a schematic depiction of actuator 14 of draw-out 6 by the s-distance (in Figs. 1-9, 12-14 there is a draw-out of arm 12) using a pinion gear. Actuator 14 is fitted with

actuator sensor 15 and acts by torque M upon transmission shaft 19 fitted with additional sensor 16 for a motion of the s-draw-out of linear guide 6 using a pinion gear. Sensor 16 for the draw-out of arm 12 can be replaced or supplemented by additional sensor 17 for a deformation of the actuator of arm 12. The very linear guide 6 can be fitted with additional sensor 18 for a deformation of linear guide 6. Typically actuator 14 is fitted only with actuator sensor 15. In order to determine linear guide 6 motion more exactly, either additional sensor 16 for a motion of linear guide 6 using a pinion gear or additional sensor 17 for an actuator deformation is used. A bigger part of a deviation of the s-draw-out of the motion measured by sensor 15 for the actuator is the draw-out actuator deformation measured by additional sensors 16 and 17. Other part of the deformation is measured by additional sensor 18 for the deformation of linear guide 6.
Accordingly, the measurement and control of linear guide 6 of the arm is arranged using a motion screw or other equipment.

Fig. 18 shows a schematic depiction of actuator 14 for a rotation of arm 12 using a belt or rope transmission by a belt or rope 20. Actuator 14 is fitted with actuator sensor 15 and acts by torque M upon transmission shaft 19 transferring a motion using a belt or rope transmission system. The rotary motion of arm 12 is measured by additional sensor 16 for a motion of arm 12 by ϕ angle on the rotational joint (marked as 5 in Figs. 1-14). Sensor 16 for the motion of arm 12 can be replaced or supplemented by additional sensor 17 for a deformation of the actuator of arm 12 on transmission shaft 19 or on a belt or rope. The very arm 12 can be fitted with additional sensor 18 for the deformation of arm 12. Typically actuator 14 is fitted only with actuator sensor 15. In order to determine arm 12 motion more exactly, either additional sensor 16 for a motion of arm 12 or additional sensor 17 for the actuator deformation is used. A bigger part of a deviation of a motion of arm 12 from a motion measured by actuator sensor 15 is a deformation of the arm actuator measured by additional sensors 16 and 17. Other part is measured by additional sensor 18 for a deformation of arm 12.

Fig. 19 shows a schematic depiction of actuator 14 of the draw-out by the s-distance (in Figs. 1-9, 12-14 there is a draw-out of arm 12) using a belt or rope transmission system by belt or rope 20 to a pinion gear. Actuator 14 is fitted with actuator sensor 15 and acts by torque M upon transmission shaft 19 transferring a motion using a belt or rope transmission system. The s-draw-out of linear guide 6 is measured by additional sensor 16 for a motion of linear guide 6 using a pinion gear for s-draw-out. Sensor 16 for the motion of linear guide 6 using a pinion gear can be replaced or supplemented by additional sensor 17 for a deformation of the actuator of arm 12 on transmission shaft 19 or on a belt or rope. Linear guide 6 can be fitted with additional sensor 18 for a deformation of linear guide 6. Typically actuator 14 is fitted only with actuator sensor 15. In order to determine a motion of the draw-out of linear guide 6 more exactly, either additional sensor 16 for a motion of a pinion gear or additional sensor 17 for an actuator deformation can be used. A bigger part of a deviation of a motion of arm 12 from a motion measured by actuator sensor 15 is a deformation of the arm actuator measured by additional sensors 16 and 17. Other part of the deformation is measured by additional sensor 18 for the deformation of linear guide 6.

Fig. 20 shows a schematic depiction of a variant of the actuator of a rotation of arm 12 as depicted in Fig. 18. However, there is a difference that here the belt or rope transmission through a belt or rope 20 is performed through inserted pulleys 23. This arrangement is possible even for a variant of the actuator of linear guide 6 in Fig. 19.

Fig. 21 shows a schematic depiction of a variant of the actuator of a rotation of arm 12 using a rope transmission by rope 20. Two ropes 20 driven by actuators 14 are acting upon rotational arm 12 rotating in rotational joint 5. As ropes 20 can act only by pulling, they have to be at least two of them and have to act upon rotational arm 12 antagonistically. Fig. 21 shows a schematic depiction of a displacement of an acting effect of ropes 20 off the axis of arms 12, so that their force can act by a momentum in rotational joint 5.

Fig. 22 shows a schematic depiction of a variant of the actuator of the s-draw-out of linear guide 6 using a rope transmission by rope 20. Two ropes 20 driven by actuators 14 are acting upon the draw-out of linear guide 6. As ropes 20 can act only by pulling, they have to be at least two of them and have to act upon the draw-out of linear guide 6 antagonistically. One of the ropes has to act through inserted pulley 23.

Fig. 23 shows a schematic depiction of an example of a typical computer-controllable embodiment of a disconnectable connection of two bodies, here gripping head 7 with connecting head 8 carrying tool 9. Gripping head 7 and connecting head 8 are fitted with connecting device 24. Connecting device 24 is remote-controlled by the control computer of the robots. The control system may be for example pneumatic, hydraulic, electric, magnetic, and operates through opening or closing attachments 25. Connecting device 24 is typically axially symmetric but not rotationally symmetric, so that after connecting a definite mutual orientation of gripping head 7 and connecting head 8 can be ensured.

During the connecting process in confined spaces, it can be difficult to achieve an accurate mutual orientation of gripping head 7 and connecting head 8 for connecting through connecting device 24 without rotational symmetry. It is necessary to enable a connection of gripping head 7 and connecting head 8 under a varied angle that is not defined in advance. This is enabled due to rotationally symmetric connecting device 24 as depicted in Fig. 24. Attachment 25 is a cylinder-shaped rotationally symmetric device that is rotationally-symmetrically placed in connecting device 24. Its principle is opening or closing attachments 25. However, this connection does not define a mutual turning of gripping head 7 towards connecting head 8 around the o-axis of a rotational symmetry of attachment 25. After connecting the mutual turning of gripping head 7 towards connecting head 8 is determined by calibration using a redundant measurement during small mutual motions of working robot 2 and supporting robot 1, when during measuring some of the actuators are disconnected, released and only their position is measured.

Fig. 25 shows a scheme of another variant of rotationally symmetric connecting device 24. Attachment 25 is a sphere-shaped rotationally symmetric device that is rotationally-symmetrically placed in connecting device 24. Its principle again is opening or closing attachments 25. However, this connection does not define a mutual turning of gripping head 7 towards connecting head 8 around all the axes passing through a center of the sphere of attachment 25. This way it is possible that the mutual turning of gripping head 7 towards connecting head 8 is not specified in any of three angles describing the mutual orientation. After connecting these three angles are determined by a redundant measurement as described in Fig. 24.

Fig. 26 shows a scheme of another variant of rotationally symmetric connecting device 24. One attachment 25 (on the right side) is a sphere-shaped rotationally symmetric device that is rotationally-symmetrically placed in connecting device 24. The second attachment 25 (on the left side) consists of three spheres the centres of which do not lie within the common straight line. The upper Figure depicts a condition before connecting when the attachments are getting closer. The lower Figure depicts a condition when all the three spheres of attachment 25 (on the left side) have touched the sphere of attachment 25 (on the right side) and have got connected. The connecting principle is a magnetic force acting upon spheres made of ferromagnetic material. However, this connection again does not define a mutual turning of gripping head 7 towards connecting head 8 around all the axes passing through the center of the sphere of attachment 25 (on the right side). This way it is possible that the mutual turning of gripping head 7 towards connecting head 8 is not specified in any of three angles describing the mutual orientation. After connecting these three angles are determined by a redundant measurement as described in Fig. 24.

Fig. 27 shows a schematic depiction of another solution of the connection of gripping head 7 to connecting head 8 carrying tool 9. Although connecting is performed as depicted in Fig. 25, handling arm 4 is connected to arm 12 of the robot by rotational joint 5, which is not driven by an actuator. Then it is movable but its movability is defined by torsion spring 26. The connection of supporting robot 1 with working robot 2 through connecting head 8 carrying tool 9 is not fixed in terms of a fixed connection of gripping head 7 to connecting head 8, but only limiting a mutual movability of robots 1 a 2. In the given case, instead of movability limiting by six degrees of freedom there is movability limiting by five degrees of freedom given by a position of a centre of rotational joint 5 and two rotations around axes perpendicular to the axis of rotational joint 5. Rotational joint 5 can be replaced by spherical joint 22, then the movability limiting is only determined by a position of the spherical joint centre.

Fig. 28 shows a schematic depiction of a different arrangement of rotational joints 5 in the structure of the robots. One rotational joint 5 is placed at the end of handling arm 4 as a part of gripping head 7. There can be more rotational joints 5 in gripping head 7. Thus actuators can be placed in gripping head 7 and accordingly in connecting head 8. Further, connecting head 8 has to comprise actuators for tool 9, if needed.

Fig. 29 shows a schematic depiction of an alternative solution as depicted in Fig. 27 based on a variant in Fig. 28. Rotational joint 5, which is not driven by an actuator but is only defined by torsion spring 26, is a part of gripping head 7.

Fig. 30 shows a schematic depiction of a method of navigation of robots 1 and 2 with carts 31 in large spaces. Measuring only motions of carts 31 is not accurate enough for an exact determination of starting positions 38 of the robots as well as of target position 33. Therefore a redundant measurement using laser tracker 34 and laser reflectors 35 is used. Laser tracker 34 emits laser beam 36, which is reflected from laser reflector 35 and through an interferometer and angular deflecting servomechanisms allows determining a relative Cartesian position of laser tracker 34 and laser reflectors 35.

In Fig. 30 working robot 2 is fitted with laser tracker 34 and supporting robot 1 is fitted with three laser reflectors 35 that do not lie within a common straight line. In addition, many laser reflectors 35 are placed in large space 30 on frame 10 and on object 39 for performing required operation, for example on a big machine.
At first, working robot 1 moves around in large space 30 and in each position measures its relative position towards all available laser reflectors 35 by laser tracker 34. These measurements are processed into information about a position of all laser reflectors 35 placed on frame 10 and on object 39 by solving overdeterminated constraint conditions describing relative positions of robots, laser trackers and laser reflectors.
Then working robot 2 is relocated within large space 30 from the initial position into starting position 38 and during its motion determines its position through laser tracker 34 towards all available laser reflectors 35 placed on frame 10 and on object 39, however, at least towards three of them not lying on the common straight line. Working robot 2 determines also a position of supporting robot 1 through measuring positions of laser

reflectors 35 by laser tracker 34 on supporting robot 1. At least three laser reflectors 35 not lying on the common straight line have to be placed on supporting robot 1, so that a position and orientation of supporting robot 1 can be determined from their position towards laser tracker 34 on working robot 2. Thus both robots 1 and 2 can be navigated to be relocated from the initial position to starting position 38 with a reach into target position 33 for carrying out the required operation. The navigation of robots 1 and 2 into target position 33 is then determined from the position of the very robots 1 and 2 through measuring their actuator sensors and additional sensors towards their starting position 38 determined by laser tracker 34 measurements.

Supporting robot 1 can also be fitted with laser tracker 34 for facilitating and accelerating the navigation (so both robots 1 and 2).

In the given examples of embodiments, gripping head 7 can be connected to connecting head 8 in various ways. These can be mechanical protrusions and mechanical jams, strutting or capture by a hydraulic, pneumatic, electrical or magnetic force. There can be spherical hollows with a magnetic clamp, hollows with protrusions and a magnetic clamp, hollows with protrusions and mechanical jam, strutting, capturing, closing shut, a simple magnetic clamp and others.

Calibration of the connection of gripping head 7 to connecting head 8 can be preferably performed so that during the connection to robot 2 in Fig 1 connecting head 8 with tool 9 is placed on the base of robot 2 in the calibration station. The calibration station is a place with an exactly determined position, which uniquely defines a position of gripping head 7 on the robot. An exact positioning of gripping head 7 can be performed through mechanical openings and protrusions or sensors. Another possibility is that after connecting both robots 1 and 2 to connecting head 8 this connecting head 8 is preferably placed into its calibration station again. When located in the calibration station, positions for the calibration of the connecting head grip are read on all the sensors of both the robots.

A confined space is a space where only (one) slender arm of a robot with a reduced cross-section can enter. A spatially limited space is a space with obstacles or other confined passageways. Confined and spatially limited spaces are called inaccessible spaces in common.

The above described methods for connecting of robots in confined and spatially limited spaces can be used e.g. for surgical robots or for machining of blades (for example of turbines or compressors) or drain conduits. The above described methods for connecting of robots in large spaces can be used for example for machining of big machines, e.g. railway wagons or airplanes.

It is possible to use more connected pairs (groups) of robots. For example surgical robotic equipment has at least two pairs of connected robots, thus there are at least two connecting heads, whereas each of them carries a tool separately and at least two tools cooperate in a patient's body.

We speak about a position and sometimes about a position and orientation. Actually, a position of an object comprises both the position of any of its point and the orientation of the object towards the coordinate system of a frame. If the orientation has to be emphasized as a turning of the object in a space, then we talk about it explicitly.

A method for increasing stiffness of connecting head 8 of the robot with tool 9 in inaccessible spaces and large spaces as described in this invention, lying in the use of at least two robots, can be used separately in a case of inaccessible spaces or large spaces or together in a case of a combination of large and inaccessible spaces.

Spherical joints 22 can consist of rotational joints 5.

Besides the earth, frame 10 can also be a body of a cosmic object, e.g. another planet, a rocket, a satellite, a space station. A motion of carts 31 along frame 10 may be a magnetic levitation and equipment 32 for attachment to frame 10 may be a magnetic clamp.

All variants described above can be combined one with another. Robots are computer controlled.

Patent Claims

1. A method for increasing stiffness of a connecting head of a robot with a working tool during its activity for carrying out a working operation in a target position in inaccessible or large spaces, characterized in that a connecting head with a working tool carried by an arm of a working robot and an arm of a supporting robot with a gripping head are moved into an inaccessible or large space, in the target position in the inaccessible or large space the robots get connected through the connecting head so that the gripping head carried by the supporting robot's arm is connected to the connecting head carried by the working robot's arm in the target position to carry out the operation by the working tool.

2. A method for increasing stiffness of a connecting head of a robot with a working tool as described in Claim 1, characterized in that the gripping head of the working robot with the connecting head with the working tool and/or the gripping head of the supporting robot is moved into an inaccessible space through a confined passageway.

3. A method for increasing stiffness of a connecting head of a robot with a working tool as described in Claim 1, characterized in that before moving the connecting heads carried by arms of robots into a target position in a large space in order to carry out an operation by a working tool, the working and supporting robot has been relocated into a starting position.

4. A method for increasing stiffness of a connecting head of a robot with a working tool as described in Claim 1, characterized in that in the target position during the working operation the overdeterminated measurement of robots is performed, which lies in simultaneous measuring in actuators of all the connected robots for more accurate determination of their positions for feedback acting upon the actuators in order to reduce deviations of the connecting head from the required position, thus leading to the higher stiffness of the connecting head.

5. A method for increasing stiffness of a connecting head of a robot with a working tool as described in Claim 4, characterized in that during the working operation in the target position the additional measurement of robots is performed, which lies in simultaneous measuring of deformations of actuators of arms and/or directly of a motion of an arm on a rotational joint or a linear guide, possibly also of deformations of arms, of all the connected robots for more accurate determination of their positions for feedback acting upon the actuators in order to reduce deviations of the connecting head from the required position, thus leading to the higher stiffness of the connecting head.

6. A method for increasing stiffness of a connecting head of a robot with a working tool as described in Claim 1, characterized in that when re-positioning robots to the starting position in a large space for carrying out an operation by a working tool, the working robot measures its position by a laser tracker towards at least three laser reflectors located inside the large space in order to facilitate navigation to the starting position and measures a position of the supporting robot in order to facilitate navigation of the supporting robot to the starting position, which lies in measuring the laser tracker position towards a position of at least three laser reflectors located on the supporting robot.

7. A device for increasing stiffness of a connecting head of a robot with a working tool with at least two robots of a serial or parallel kinematic structure fitted with a gripping head for attaching to the connecting head, where the connecting head is fitted with at least two attachments for connecting to gripping heads of at least two robots particular arms of which are connected together through rotational joints and linear guides in a way as described in Claim 1, characterized in that at least one of robots (1, 2) is kinematically redundant, comprising more rotational joints (5) or linear guides (6) than six, or handling arm (4) of at least one of robots (1, 2) is of a slender design or at least one of robots (1 and 2) is fitted either with laser tracker (34) or at least three laser reflectors (35).

8. A device for increasing stiffness of a connecting head of a robot with a working tool as described in Claim 7, characterized in that attachments (25) for attaching connecting head (8) to gripping head (7) of robots (1 and 2) either on the side of connecting head (8) or on the side of gripping head (7) are rotationally symmetrical or comprise rotational joints or linear guides without actuators.

9. A device for increasing stiffness of a connecting head of a robot with a working tool as described in Claim 7, characterized in that at least one of robots (1 and 2) is fitted with at least one additional sensor represented by sensor (16) for a motion of arm (4) on rotational joint (5) or linear guide (6) or by sensor (17) for a deformation of an actuator of arm (4) or by sensor (18) for a deformation of arm (4).

10. A device for increasing stiffness of a connecting head of a robot with a working tool as described in Claim 7, characterized in that at least one of the robots is placed on movable cart (31) fitted with equipment (32) for attaching to frame (10).

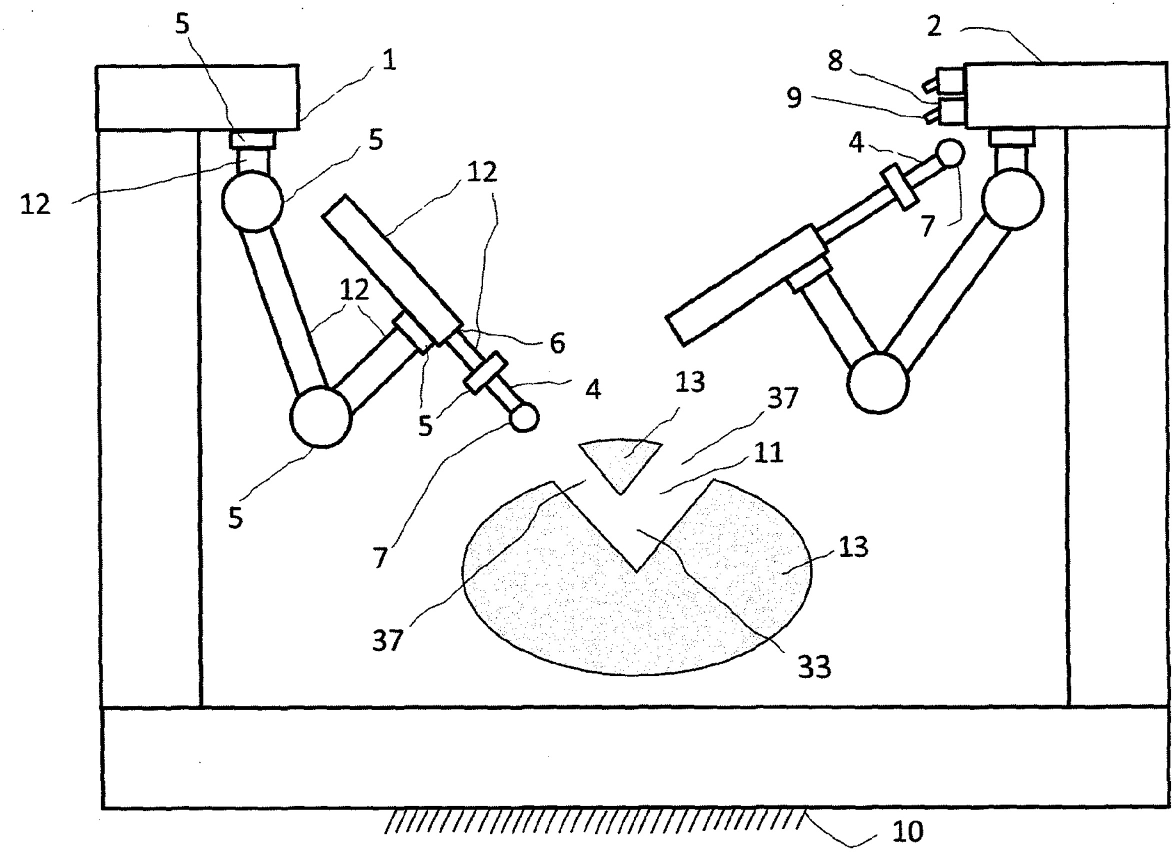
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Fig. 1

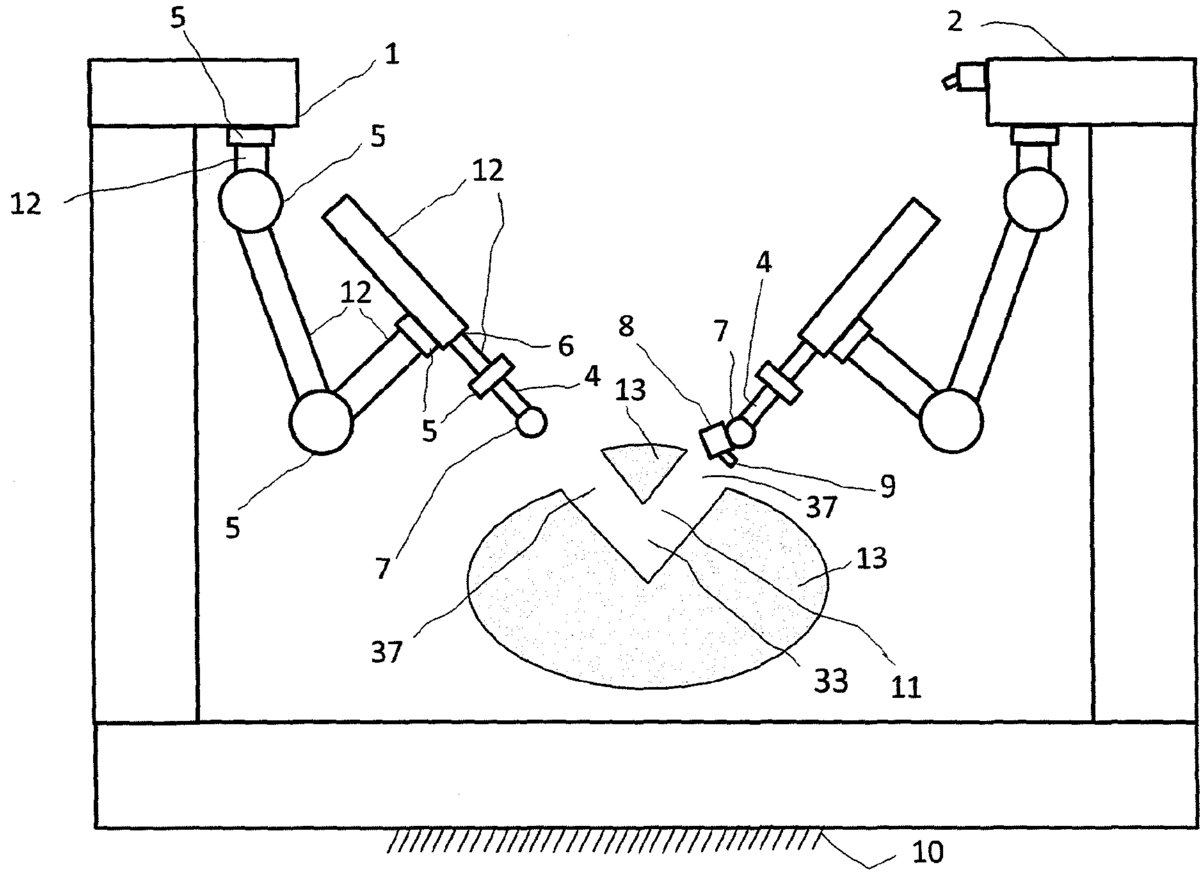
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Fig. 2

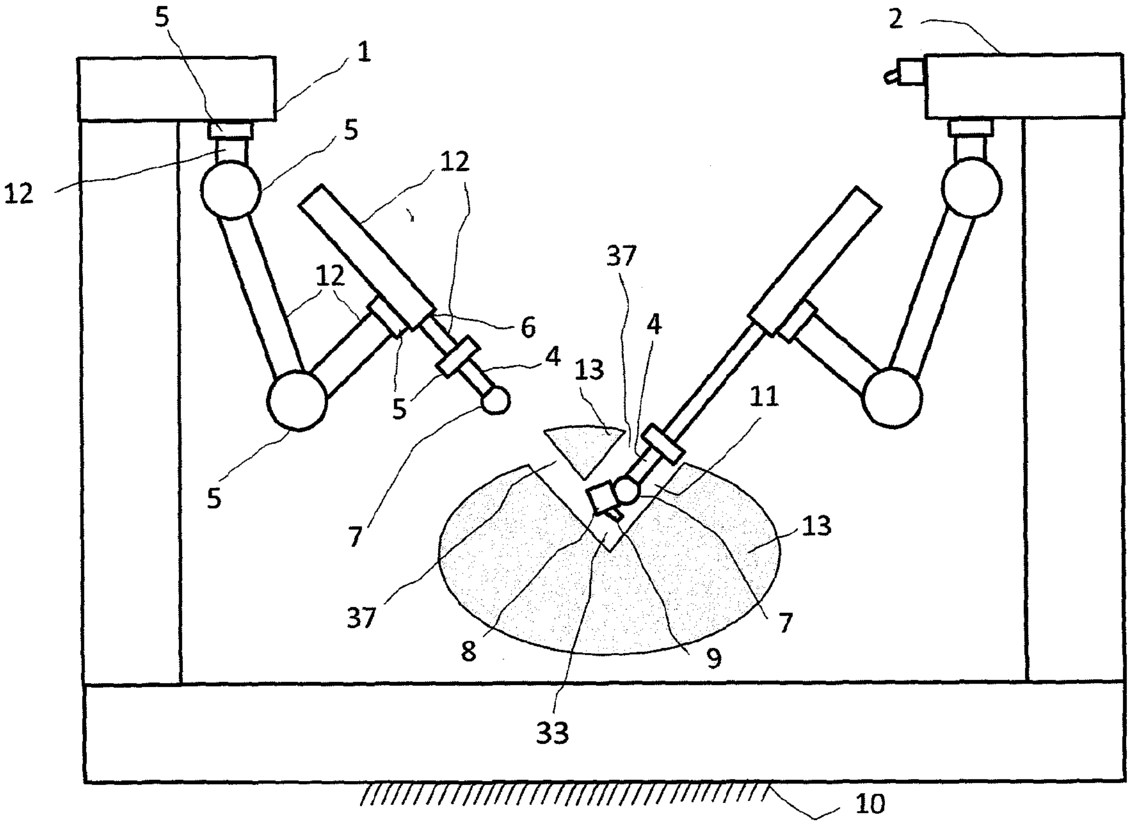
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Fig. 3

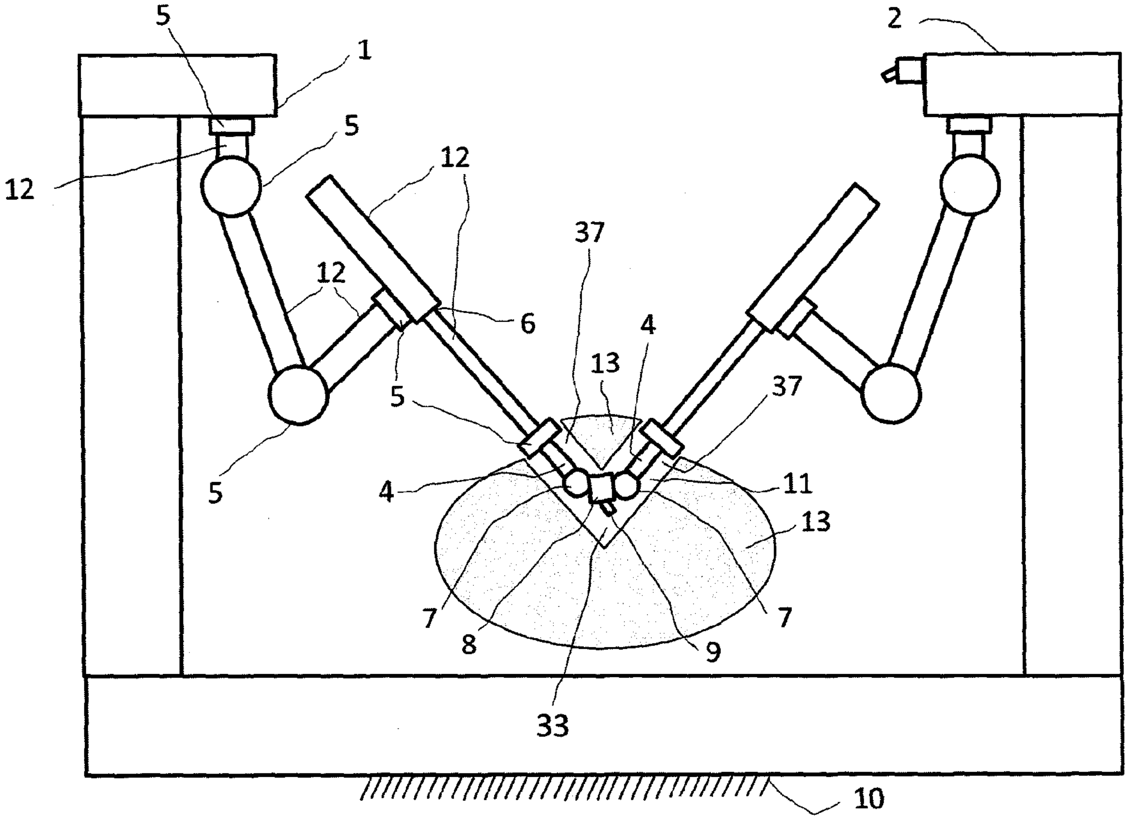
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Fig. 4

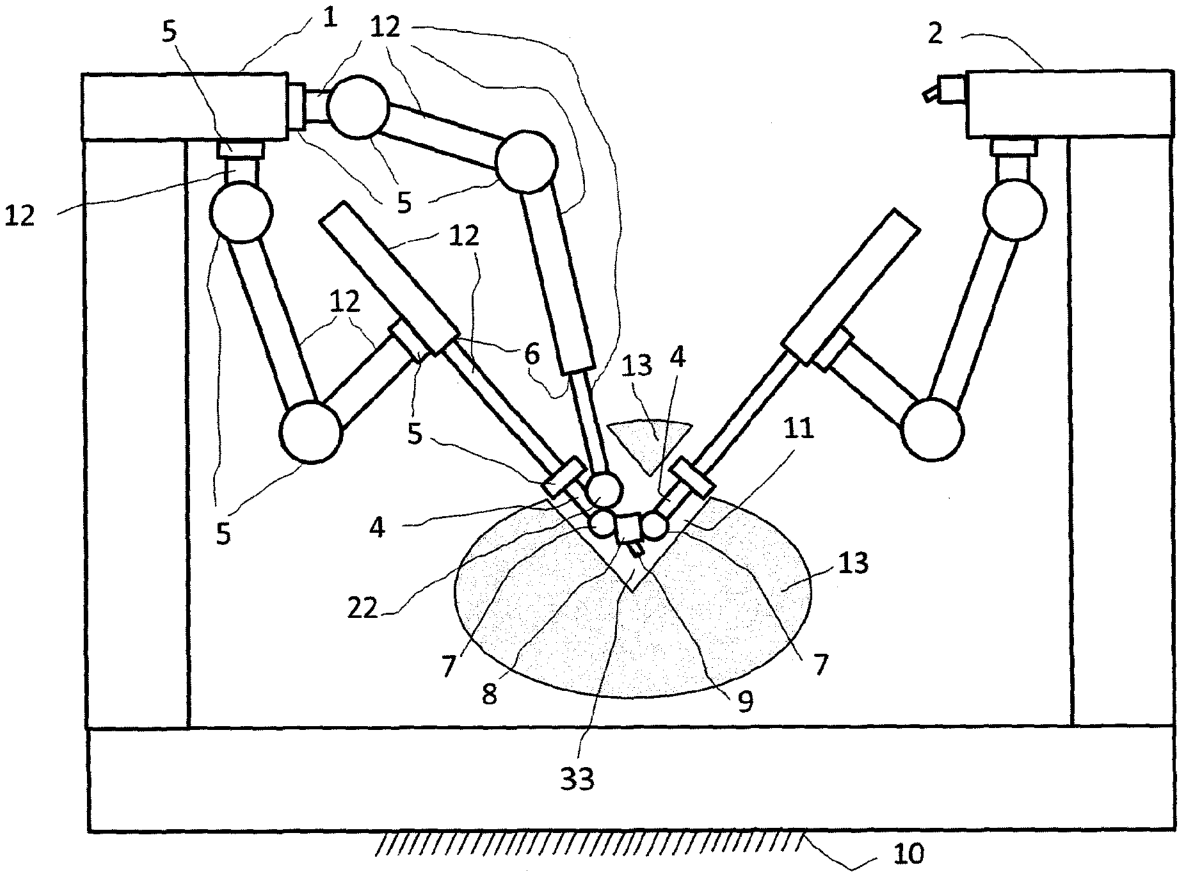
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Fig. 5

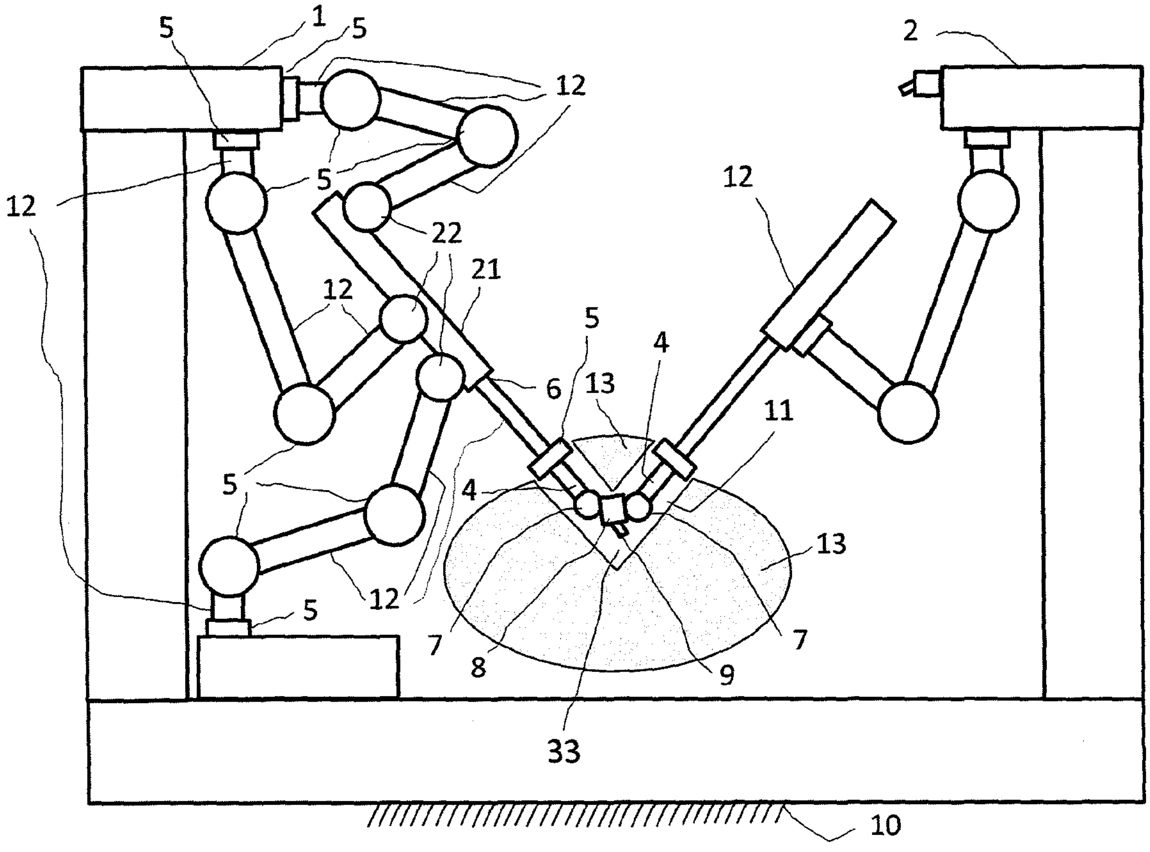
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Fig. 6

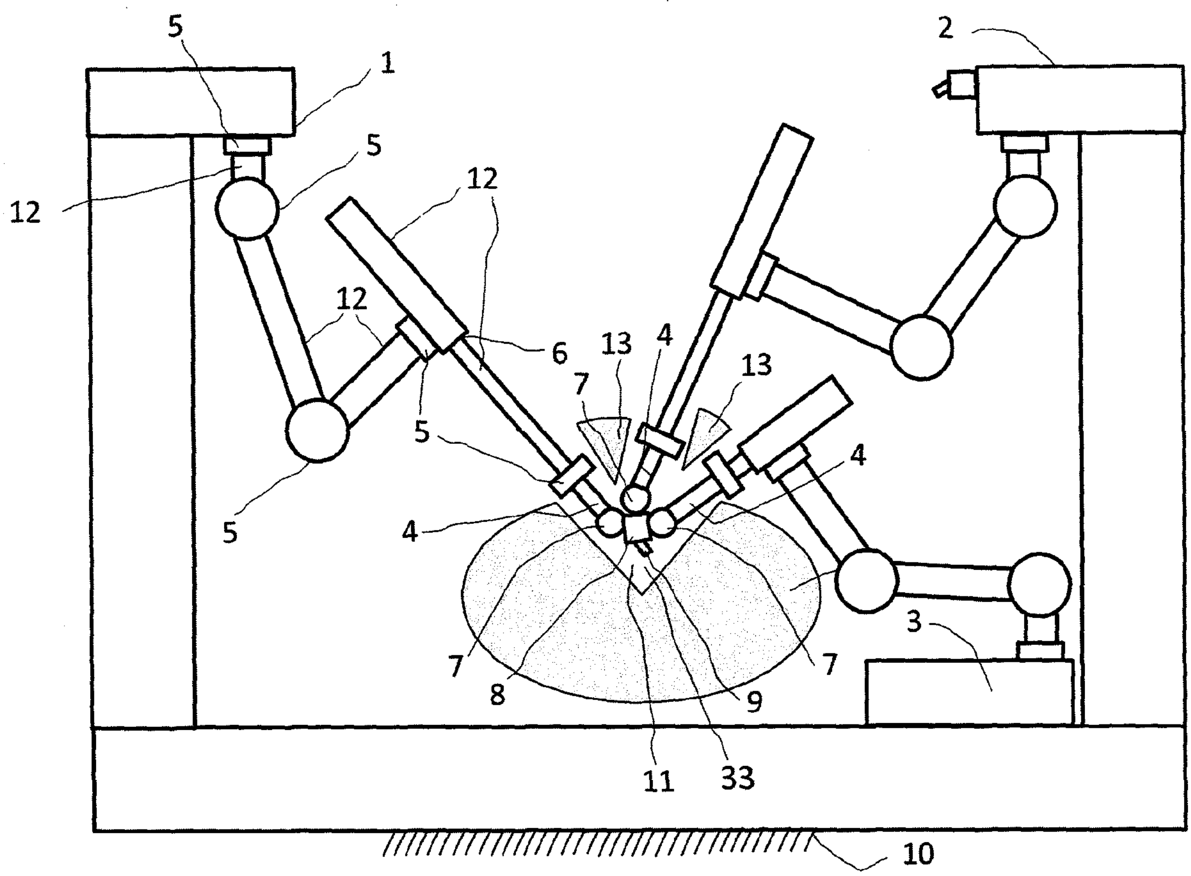
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Fig. 7

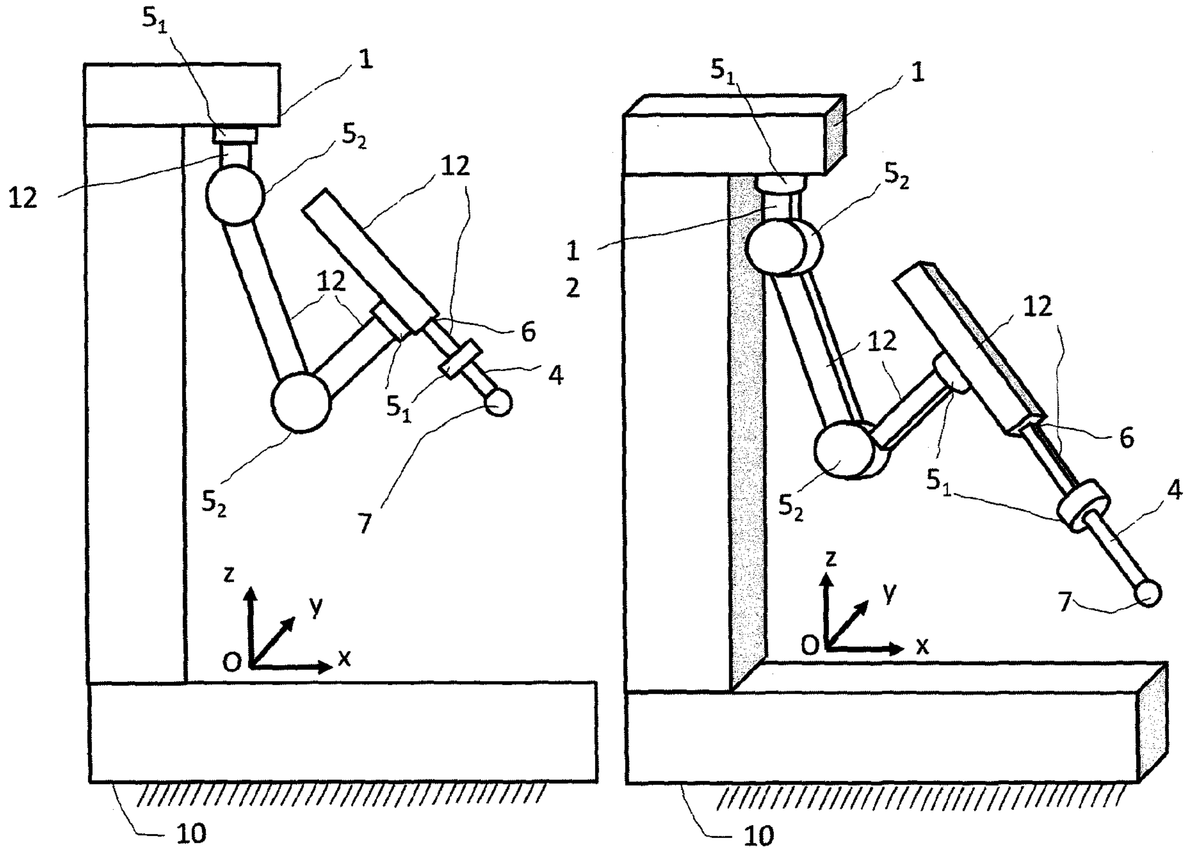
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Fig. 8

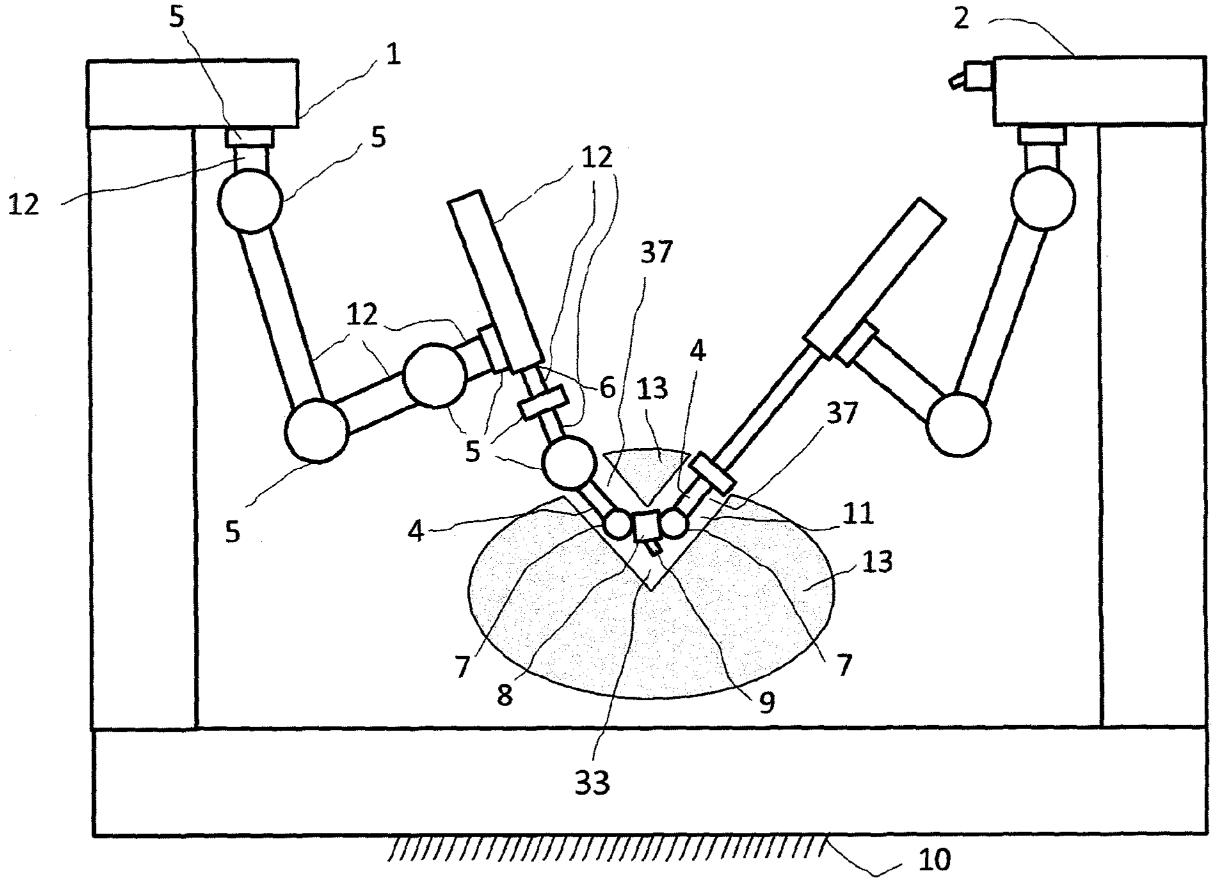
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Fig. 9

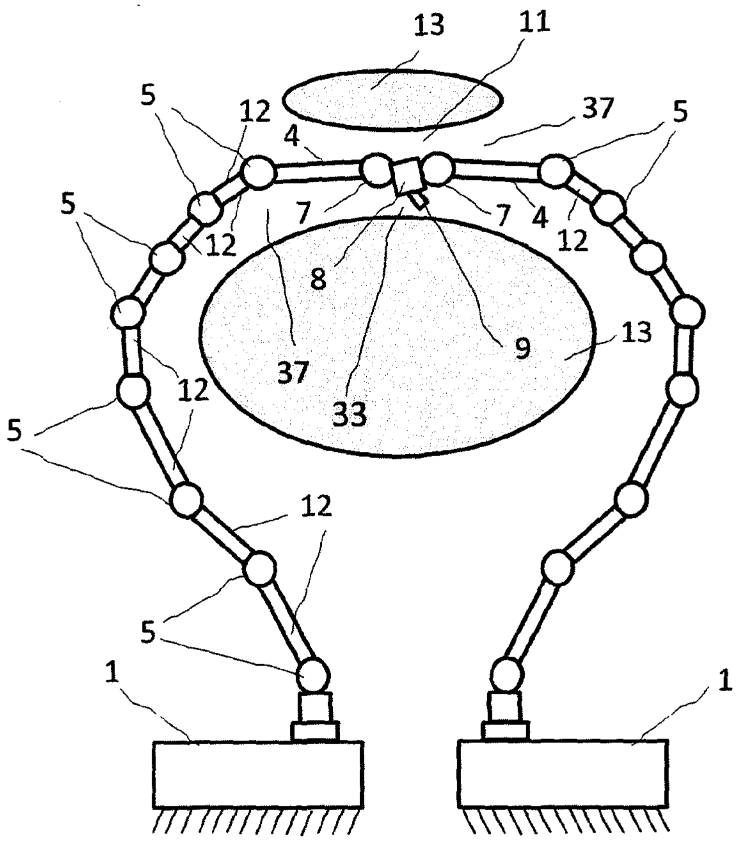
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Fig. 10

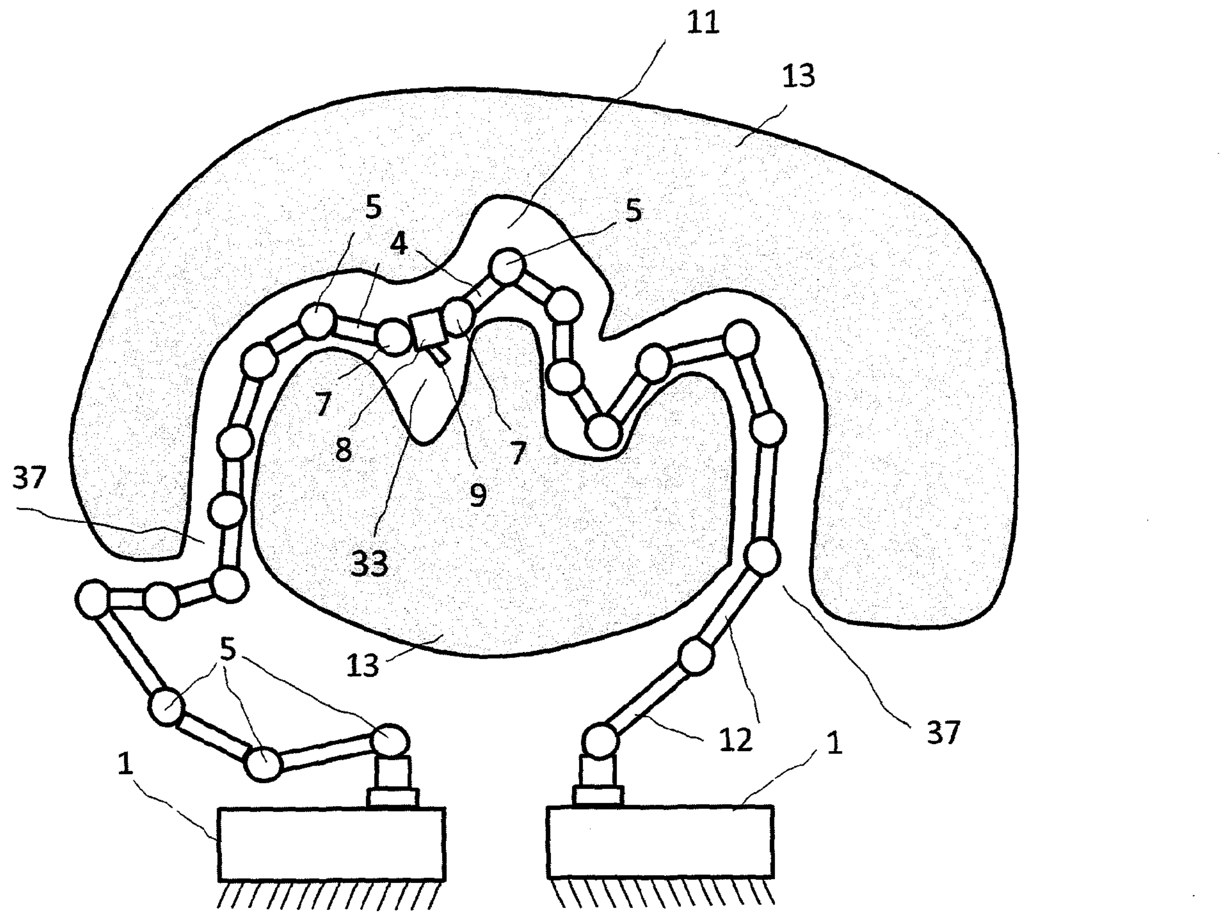
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Fig. 11

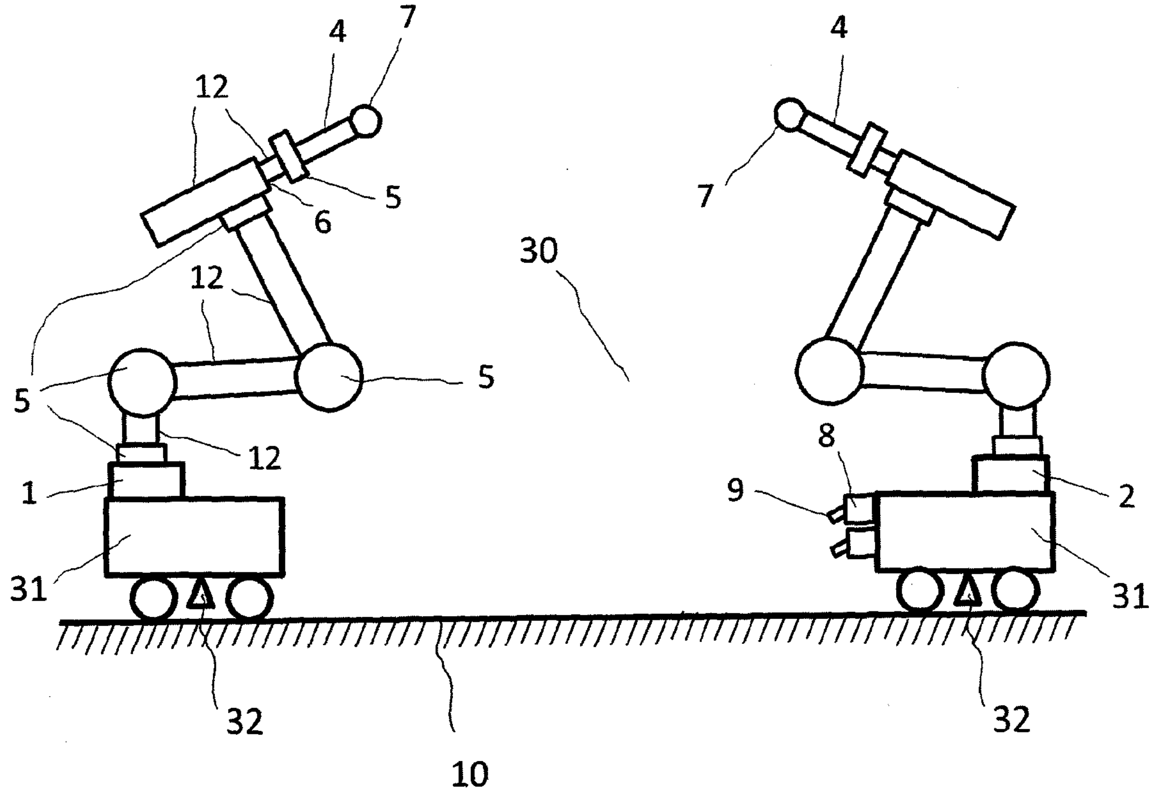
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Fig. 12

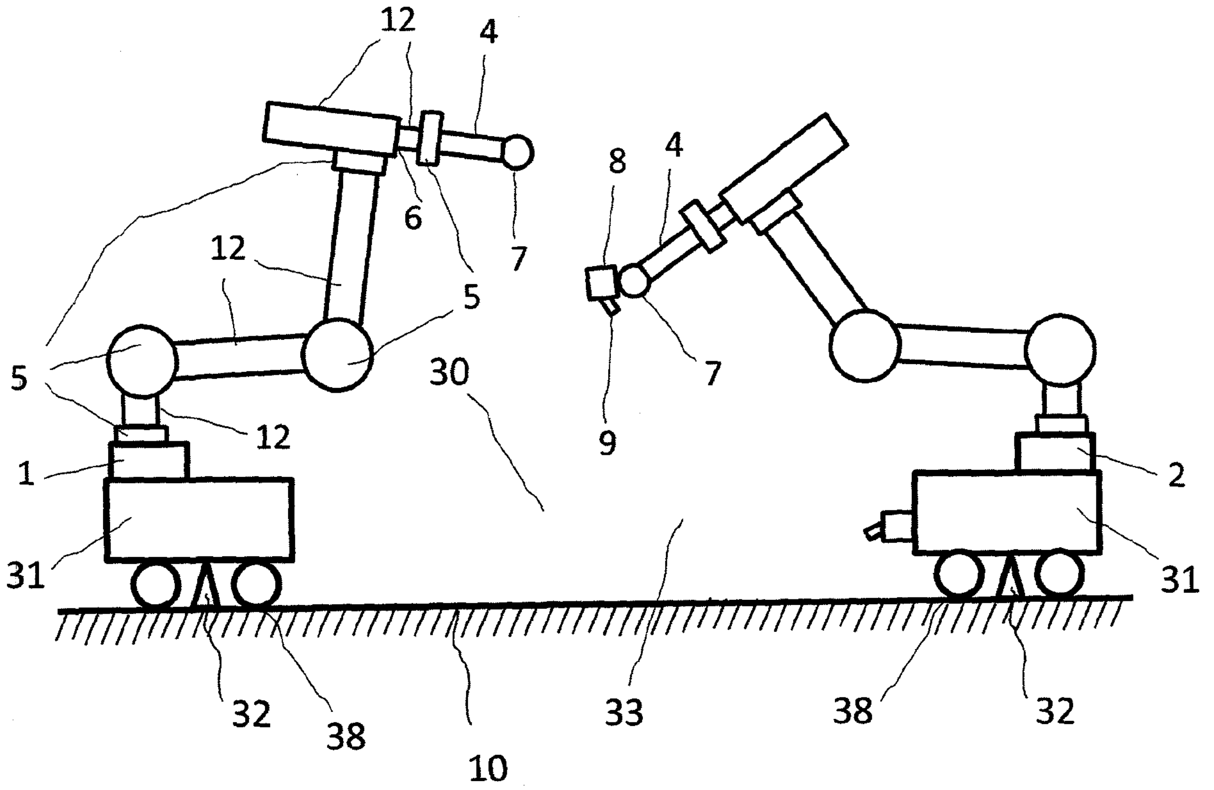
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Fig. 13

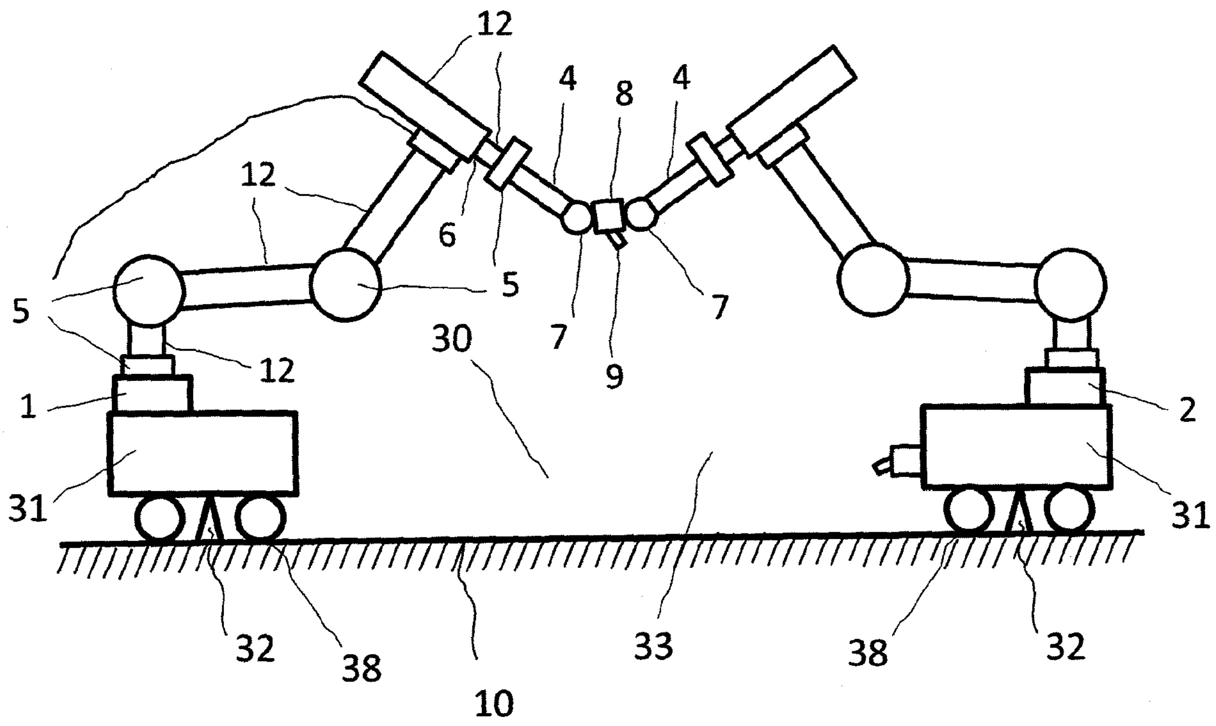
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Fig. 14

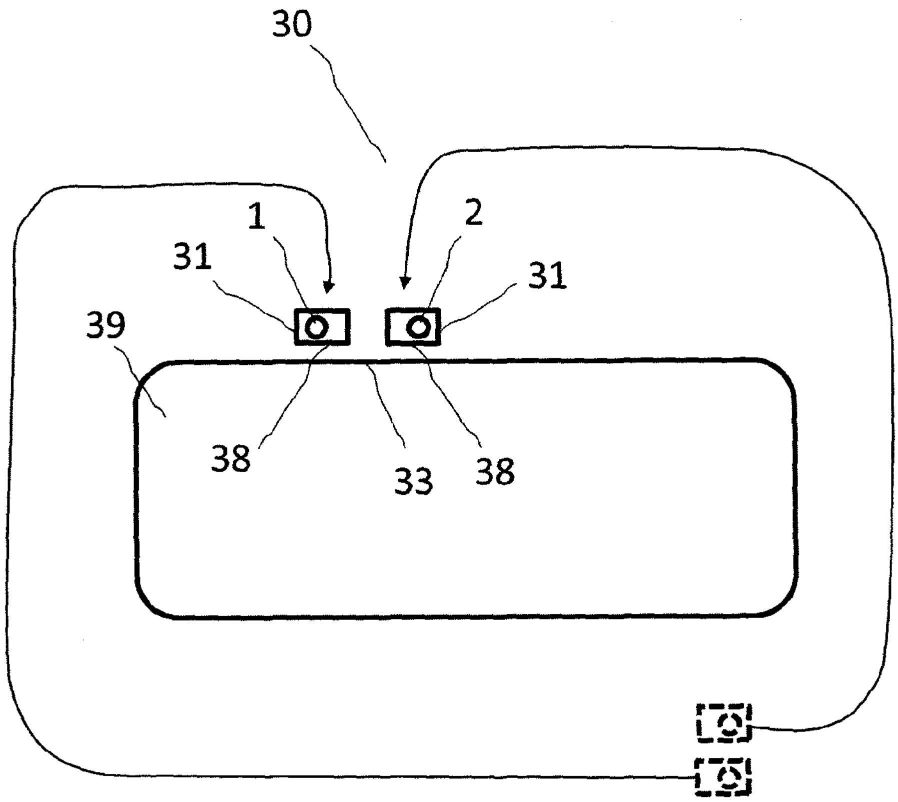


Fig. 15

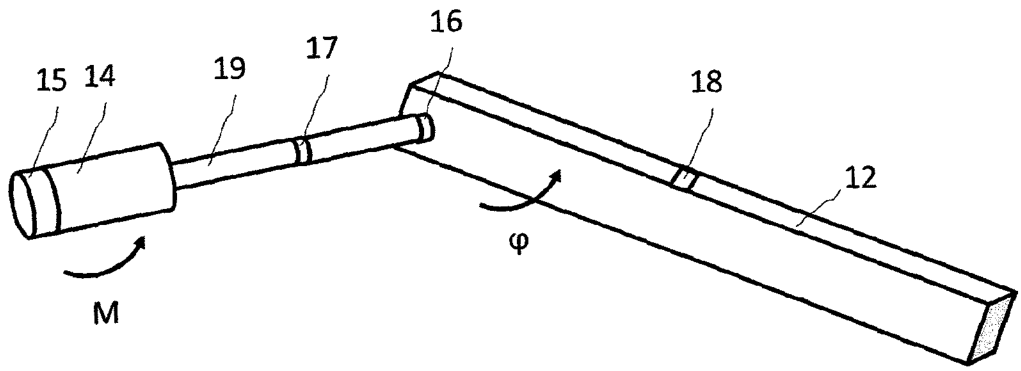


Fig. 16

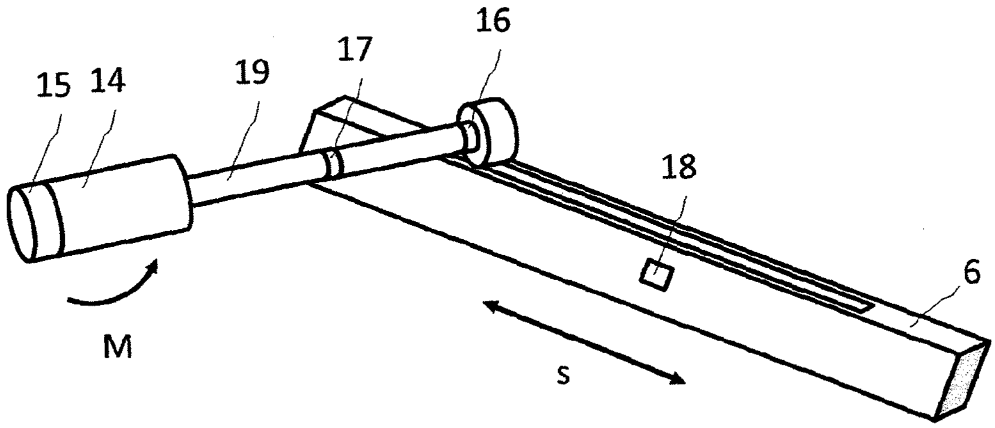


Fig. 17

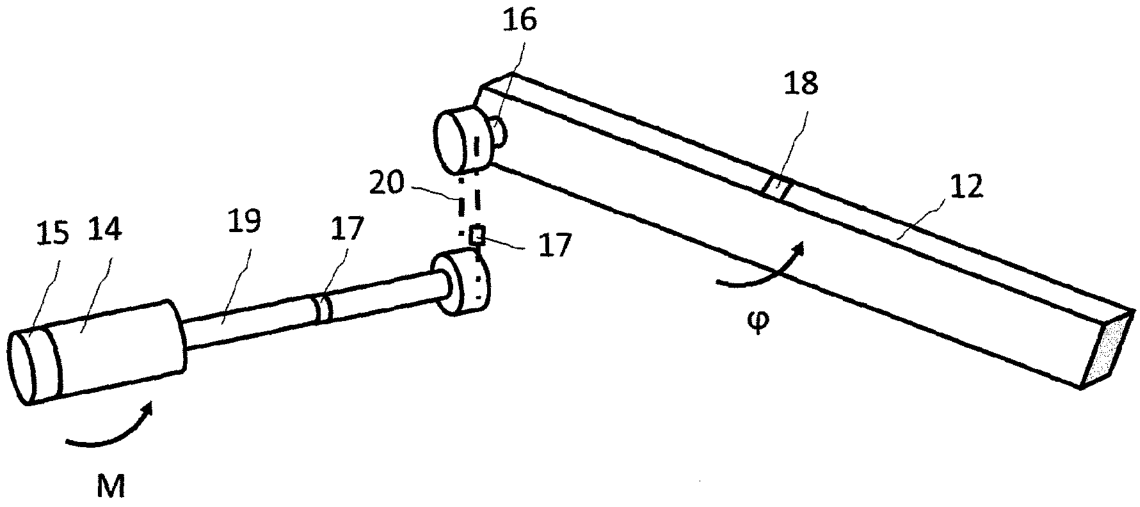
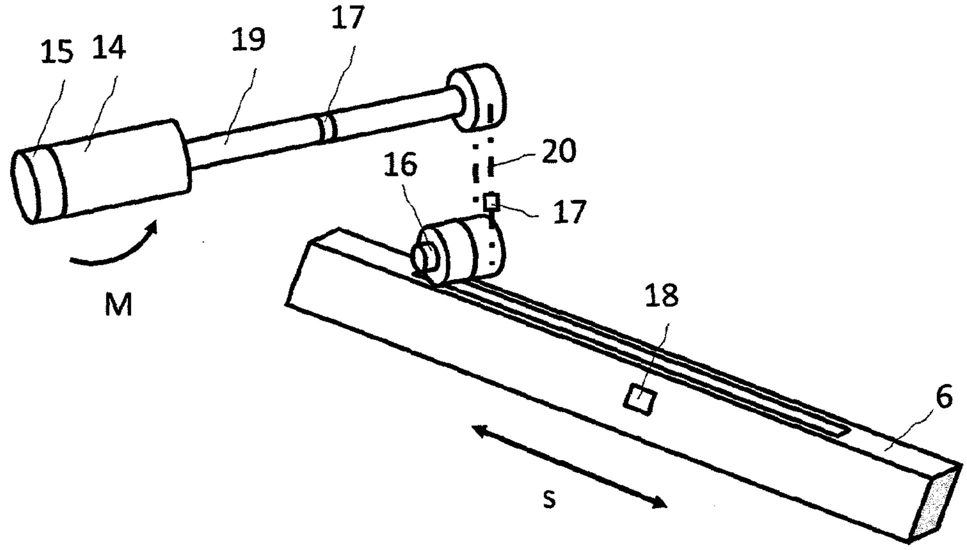


Fig. 18



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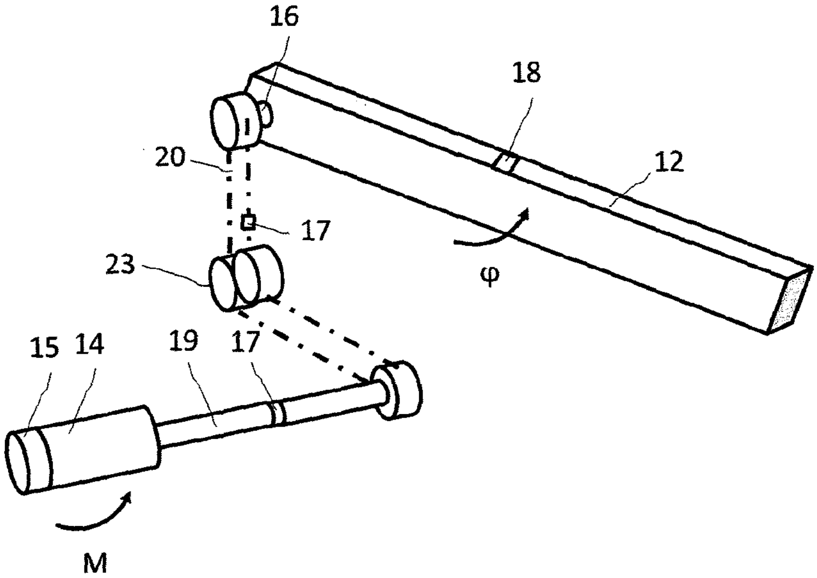

Fig. 20

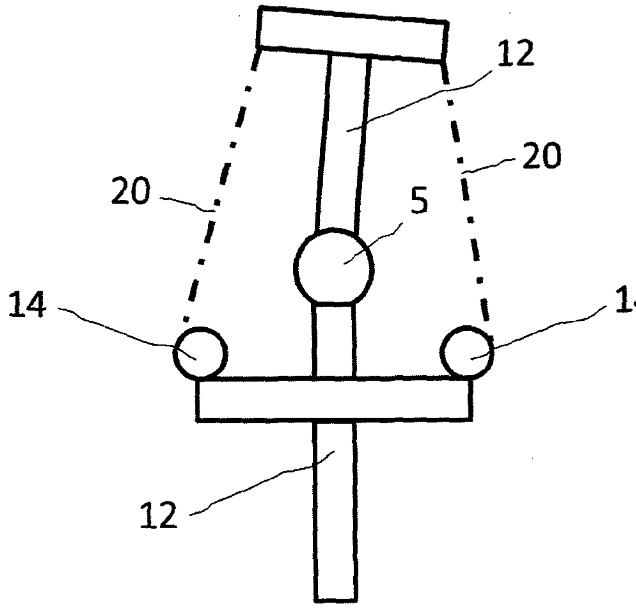

Fig. 21

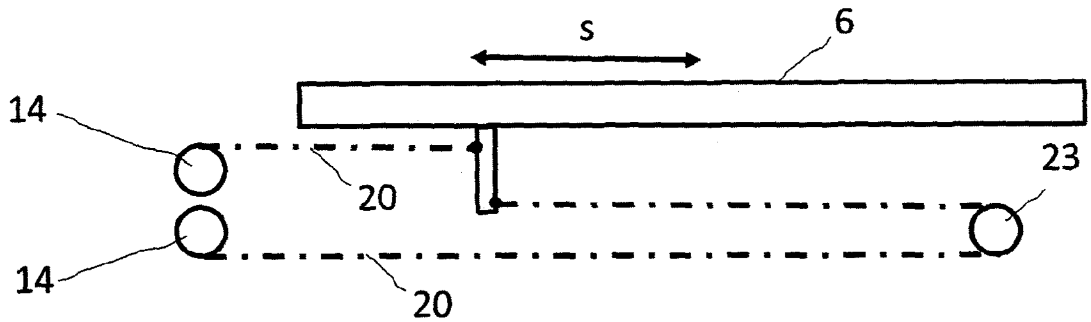

Fig. 22

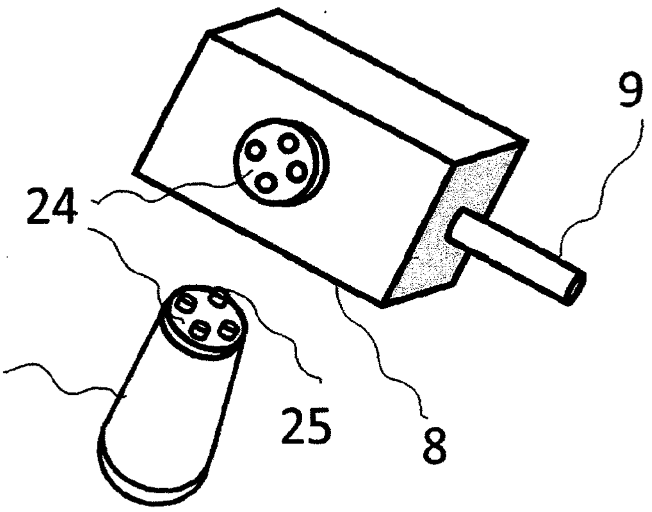

Fig. 23

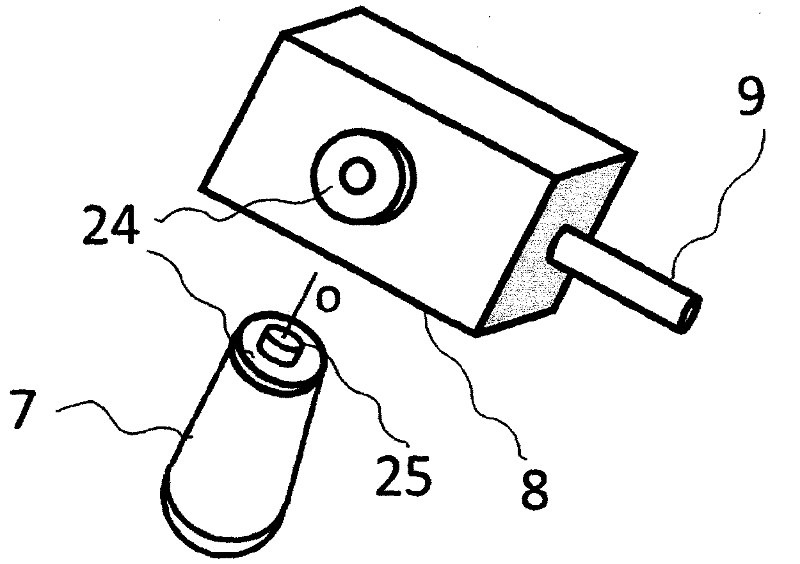

Fig. 24

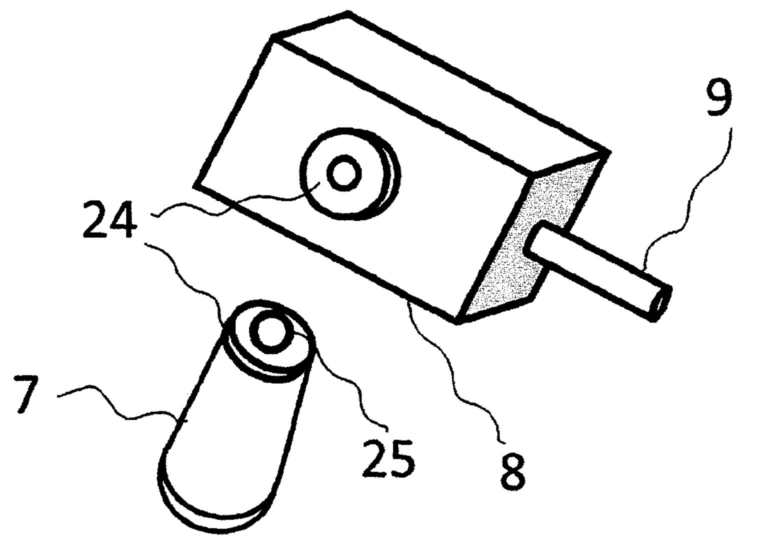

Fig. 25

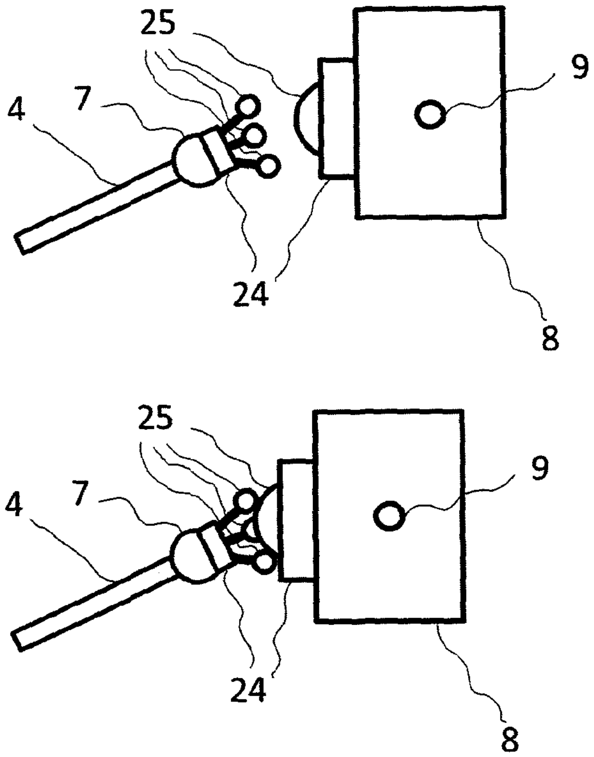

Fig. 26

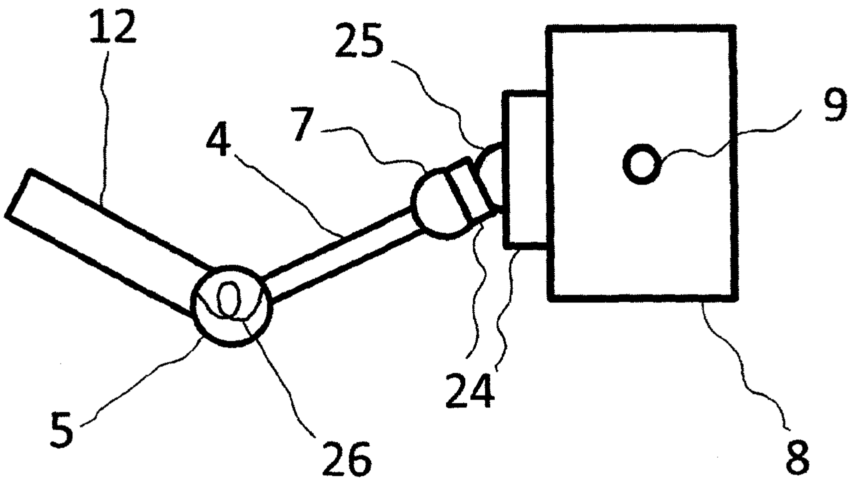

Fig. 27

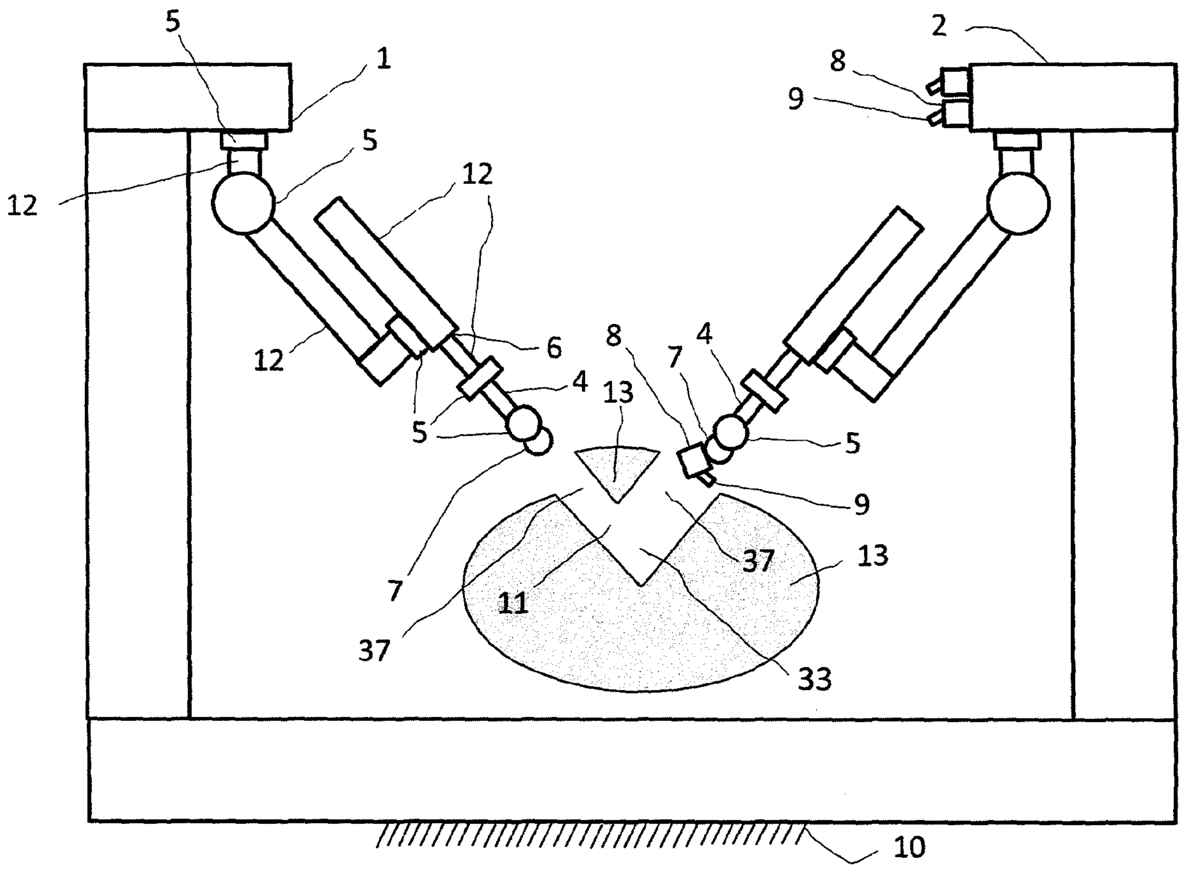

Fig. 28

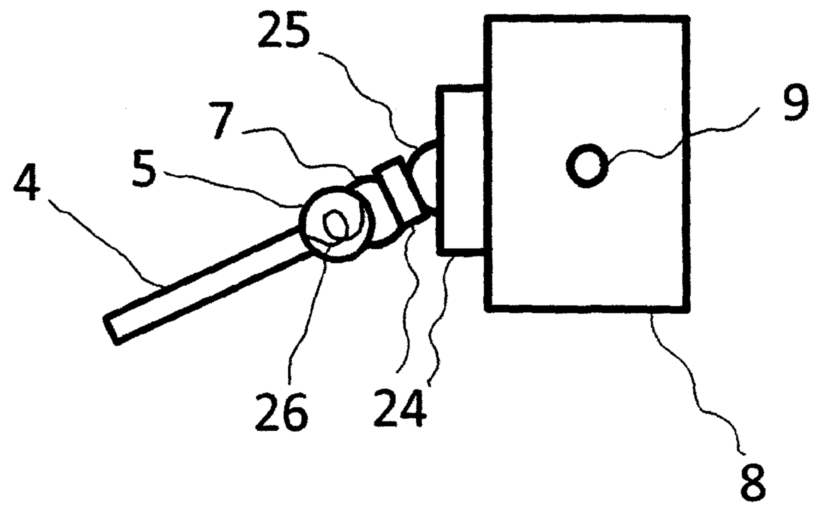

Fig. 29

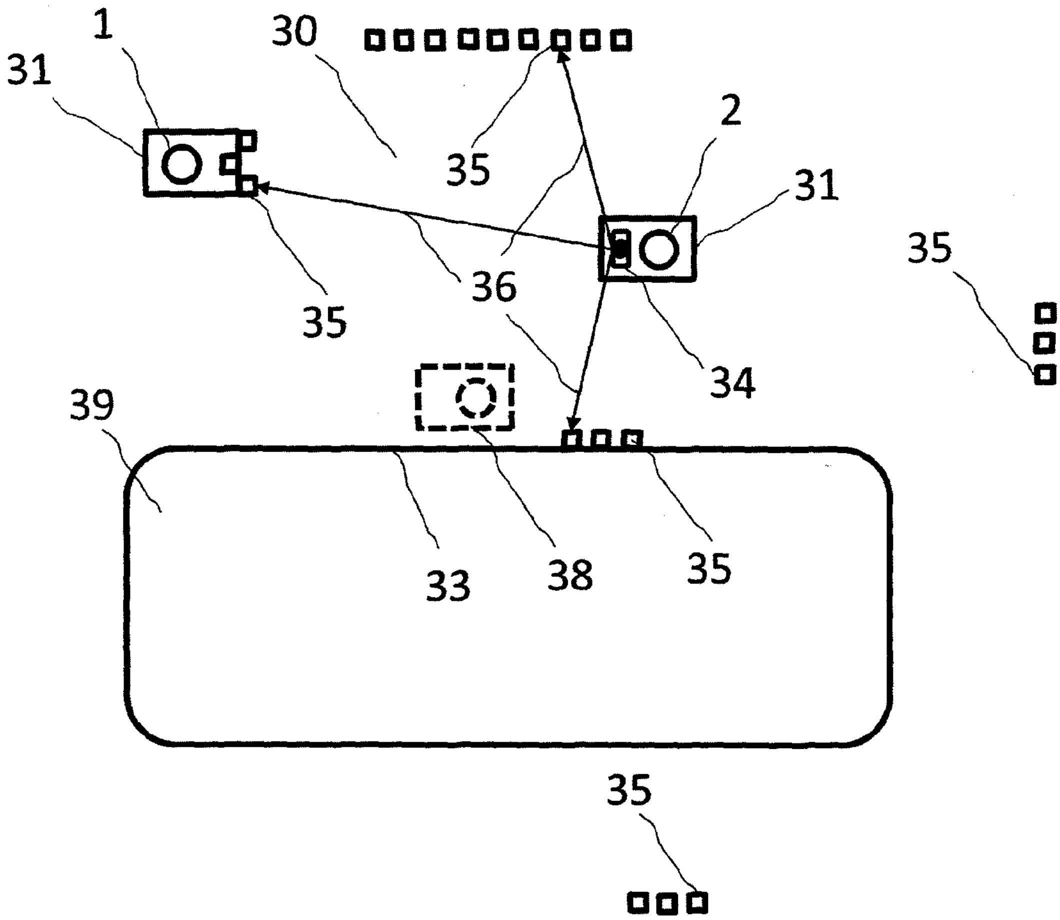

Fig. 30

INTERNATIONAL SEARCH REPORT

International application No
PCT/CZ2021/000005

A. CLASSIFICATION OF SUBJECT MATTER
INV. B25J9/16
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2013/013109 A1 (BRUDNIOK SVEN [DE] ET AL) 10 January 2013 (2013-01-10) figure 1 paragraph [0006] paragraph [0008] paragraph [0011] paragraph [0025] -----	1,4,5, 7-10 3,6
X	JP H06 262553 A (HITACHI LTD) 20 September 1994 (1994-09-20) paragraph [0001] paragraph [0019] paragraph [0025] -----	1,2
Y	EP 2 732 934 A2 (CVUT V PRAZE FAKULTA STROJNÍ [CZ]) 21 May 2014 (2014-05-21) paragraph [0015] - paragraph [0016] -----	3,6
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[X] Further documents are listed in the continuation of Box C.

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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International application No
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