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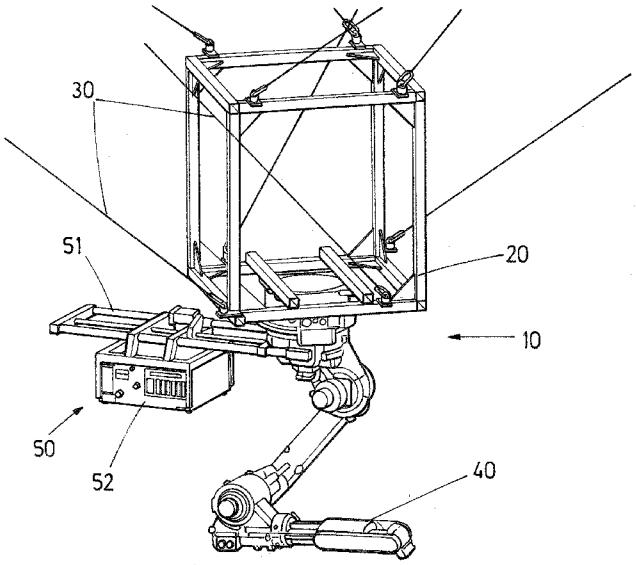

FIG.2

(57) Abstract: The invention refers to a cable-driven parallel manipulator (10) comprising: - a support structure; - a cable system (30) mounted on the support structure; and - a mobile platform (20) connected to the cable system (30) whereto a load is attachable; - the cable system being controlled by a control unit to position and orientate the mobile platform (20) and/or to apply wrenches on the mobile platform (20); and further comprising: - at least one movable device (50, 51, 52, 50', 51', 52') mounted on the mobile platform (20); - a control module configured to generate an instruction to move the movable device (20) for displacing an overall center of mass of all of: the mobile platform, the at least one movable device and the load, such that, upon moving the movable device (20), the overall center of mass is within a predetermined region (101). The invention also refers to a method for stabilizing a load of a cable-driven parallel manipulator (10).

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CABLE-DRIVEN PARALLEL MANIPULATOR

TECHNICAL FIELD

The present invention is related to the field of manipulators, and more particularly, cable-driven parallel manipulators comprising a plurality of elongated and flexible traction elements, generically referred to as "cables" in the present document.

STATE OF THE ART

In the present text, the term "cable" is used to encompass any kind of flexible traction element that can be used in the context of the present invention, for example, cables, tendons, ropes, wires, strings, chains, belts, etc.

Cable-driven parallel manipulators are a particular type of parallel-link manipulators in which the rigid links are replaced by cables. Several cables of varying lengths connect a usually mobile object, here called the mobile platform, to a generally stationary one, here referred to as the base support.

As it is well-known in the state of the art (for example, cf. P. Bosscher et al., *Wrench-feasible workspace generation for cable-driven robots*, IEEE Trans. on Robotics, 22(5):890–902, 2006; M. Gouttefarde et al., *Interval-analysis-based determination of the wrench-feasible workspace of parallel cable-driven robots,* IEEE Trans. on Robotics, 27(1):1–13, 2011) within the so-called wrench-feasible workspace of the manipulator, appropriate control of the cable lengths and/or tensions allows the mobile platform to be positioned and oriented (as desired within known limits) and/or forces and moments (i.e. wrenches) at the mobile platform to be balanced, while keeping the cable tensions within prescribed bounds. (In mechanics, a wrench is a force and moment system in which the force and the moment are parallel. Every system of forces and moments can be reduced to a wrench. Note that "torque" and "couple" are synonyms of "moment"). These bounds on the cable tensions consist of a minimum admissible tension and a maximum admissible tension. The tension in each cable of the cable-driven parallel manipulator shall be, on the one hand, larger than the minimum admissible tension and, on the other hand, smaller than the maximum admissible tension. If this constraint on the cable tensions is not satisfied, the safety and proper operation of the manipulator may be compromised. In fact, the minimum admissible tension is set to a non-negative value which represents the fact that each cable can pull, but not push (a negative cable tension would mean that the cable is pushing). The maximum admissible tensions are set by the maximum admissible stress in mechanical parts, e.g. in the cables or in routing pulleys, or by the maximum torques of the manipulator actuators.

Methods and means well known in the art permit the automatic or manual control of

all the desired degrees of freedom of the mobile platform in various settings, including decentralized model-based control and sensor-based control, implemented by way of various types of controller (PID, adaptive, robust, ...) and sensors (encoders, force sensors, ...). As it is also well-known in the current art, various methods and means exist to pay out and take up cables and/or to keep the cables tensed, to route a cable from a winch to the element (eyelet, swiveling pulley, etc.) from which it extends toward the mobile platform, to select suitable cable attachments onto the mobile platform, to measure the cable tensions, and to actuate crane trolleys which may be used in conjunction with a cable-driven parallel manipulator.

Cable-driven parallel manipulators possess a number of advantageous characteristics including modularity, scalability, re-configurability, and the ability to cover a large dimension workspace (typically up to several tens of meters) and to handle heavy loads (typically, several hundreds of kilograms). Thus, their use in industrial applications involving very large dimensions (10 to 100 m) and/or heavy loads (100 to 1000 kg) may be relevant and there are numerous potential applications of cable-driven parallel manipulators, including applications where controlling and/or constraining the possible motions of a load/tool is needed. They compete mostly with lifting equipment on this specific field of application, providing the advantage of suppressing sway and resisting to solicitations in all direction of forces and moments, and thus the possibility of being operated autonomously as a proper robot.

Examples of large-dimension applications are construction, maintenance and/or dismantling of large metallic structures, airplanes, ships, buildings, dams, or (nuclear) power plants. Currently, most of these applications are labor-intensive and involve many different tasks. If they need to be accomplished by a robotic system, a robust combination of capabilities in motion, dexterity and direct physical interaction with the environment around the robot is required.

Hence, if cable-driven parallel manipulators are to be used in such applications, they may have to be equipped with on-board devices that provide the required local dexterity. The fact that they can be equipped with such devices is one major difference with standard lifting systems, which swaying behavior does not allow this use, and therefore a major differentiating point for cable-driven parallel manipulators in the lifting industry. This leads to a mobile manipulator system like the one shown in Figure 1, which consists of a cable-driven parallel manipulator 1 carrying a conventional robotic arm 2 mounted on its mobile platform 3. This idea of mounting an active mechanical device on the mobile platform of a cable-driven parallel manipulator is known, as shown for example in US patents No. 4666362 and 6566834. However, in these examples of robotic arms operating on-board a mobile platform

of a cable-driven parallel manipulator, the robotic arm is a small arm (with respect to the platform), it does not move, or it moves slowly, and there is no mechanical interaction or contact between the arm end-effector and its environment. Then, the forces and moments generated by the small robotic arm, if any, on the mobile platform of the cable-driven parallel manipulator, remain small enough for their action to be considered negligible. Consequently, the statics and dynamics of the cable-driven parallel manipulator are not substantially disturbed by the on-board robotic arm, thereby preserving its nominal operation conditions.

Patent document US 4710819 describes a suspension system for supporting and conveying equipment, such as a camera. The equipment support member (the mobile platform) is suspended by flexible elements, e.g. cables, so as to possess three translational degrees of freedom. In addition, the equipment support member contains means that allow the conveyed equipment and the equipment support member to be rotatable relative to each other (for instance, by means of a gimbal). The purpose of this relative rotation is to controllably isolate the conveyed equipment from the angular movement of the equipment support member, in particular to keep the conveyed equipment perpendicular to the earth. The conveyed equipment may have its own means of changing and controlling its orientation. The active devices on-board the mobile platform (equipment support member) are used to keep the orientation of the conveyed equipment independent of the orientation of the mobile platform. The motions of the movable elements on-board the mobile platform are a consequence of a change of orientation of the mobile platform.

Patent document US 4883184 relates to a stabilized load lifting device consisting of a load platform (mobile platform) suspended from a carriage by three pairs of cables. All the six cable lengths are adjusted by one unique winch in order to lower or raise the load platform so that the cable lengths are not independently controlled. It is possible to modify the position and orientation of the carried load relative to the mobile platform so as to modify the location of the center of mass of the carried load with respect to the mobile platform. As a result, the movement of the center of mass has an impact on the tension in the cables, which is thus controlled by the movement of the movable device, but there is no impact in the tension of the actuator.

Patent document US 20080054836 relates to means for the displacement along three degrees of freedom of an object, typically a camera, by means of a cable-driven parallel manipulator. In particular, in some embodiments, the camera is fixed at the end of a boom which angular position in space is set by the position of a counterweight. The counterweight can be synchronized by the telescopic motion of the boom to keep said boom at constant orientation during movement. The tilting movement is out of the range of possibilities by the cable-driven parallel manipulator; the counterweight is here a means to actuate this degree

of freedom despite the inability of the cable-driven parallel manipulator to do so. Retroactively, movements of the counterweight do not have any impact on the tensions in the cables, which all of them have a single actuator.

As already pointed above, the cable tensions shall remain within prescribed admissible bounds (minimum and maximum admissible tensions) to ensure safety and a proper functioning of the cable-driven parallel manipulator. As well-known in the art, this constraint on the cable tensions yields a bounded set of mobile platform wrenches (forces and moments) that the cables can balance with tensions remaining within the prescribed admissible bounds, i.e. with admissible cable tensions. In the sequel, this bounded set of mobile platform wrenches is referred to as the *feasible wrench set* and a platform wrench lying inside this set is referred to as a *feasible wrench*. In existing cable-driven parallel manipulators, for given minimum and maximum admissible cable tensions, the feasible wrench set is only altered by the pose (position and orientation) of the mobile platform since it depends on the configuration of the cables around the platform. Hence, for a given mobile platform pose, if a specific platform wrench is outside of the feasible wrench set, this wrench cannot be produced by the cables with admissible cable tensions. This wrench infeasibility is often a significant issue, notably when operating a mechanical manipulator on-board the cable-driven manipulator mobile platform. Indeed, for typically stretched-out postures of the on-board manipulator, the moments applied onto the mobile platform can lead to wrenches outside of the feasible wrench set. Such postures, though potentially useful, can then not be authorized without compromising the safety and proper functioning of the machine. The same issue may arise when dealing with picking and placing a heavy load with a cable-driven parallel manipulator. In some cases, the load needs to be picked with an offset distance, or on the sides of the platform, or needs to be inclined from the vertical position, leading to possibly off-centered gravity loads that generate a moment. In the current state of art, the only way to modify the feasible wrench set with the objective of making the required wrench feasible is to change the pose of the cable-driven parallel manipulator, or to consequently increase the weight on board the cable-driven parallel manipulator in order to avoid low tension in the cables. However, the size and shape of the feasible wrench set change significantly only if the mobile platform pose is substantially modified which is most of the time not permitted by the task to be accomplished; on the other hand, oversizing the embarked weight cannot solve the issue in some complex positions, while being widely inappropriate in terms of power and size versus the task at hand.

In general terms, the wrench resulting from a load and its picking position on the mobile platform may prove to be out of the feasible wrench set for a given design of cable-driven parallel manipulator. Hence, when dealing solely with the cable tensions within the

prescribed bounds, nothing can be done to make the required wrench feasible: usable postures of the on-board mechanical manipulator shall be (strongly) restricted, picking and placing scenarios need to be redefined, or the platform needs to be further loaded with inert weight, leading to an oversized platform with respect to the task at hand.

Therefore, there is a need for cable-driven parallel manipulators with increased capabilities going beyond current nominal physical constraints, e.g., to be capable of handling (translating, rotating, securing, etc.) heavy and large objects or capable of balancing the increased wrenches demanded by, for instance, an on-board mechanical manipulator.

DESCRIPTION OF THE INVENTION

The invention provides a cable-driven parallel manipulator which includes means for an active control of the location and of the motion of the overall center of mass (also referred to as overall CoM in the present document) by actively controlling the locations and the motions of the centers of mass of the specific elements of the cable-driven parallel manipulator. This additional means for an active control of the overall CoM comprises one or several movable devices placed on-board the mobile platform of the cable-driven parallel manipulator, whose positions are computer-controlled so as to position the overall center of mass into a suitable region of space.

So the present invention relates to a cable-driven parallel manipulator which comprises:

- a support structure;
- a cable system mounted on the support structure;
- a mobile platform connected to the cable system, whereto the load is attachable;
- the cable system being controlled by a control unit to position and orientate the mobile platform and/or to apply forces and/or moments (i.e. wrenches) on the mobile platform.

According to a first aspect of the invention, the cable-driven parallel manipulator further comprises:

- at least one movable device mounted on the mobile platform; and,
- a control module configured to generate an instruction to move the movable device for displacing an overall CoM of the cable-driven parallel manipulator, such that, upon moving the movable device, the overall CoM stays inside a predetermined region, which is the CoM feasible region; the overall CoM of the cable-driven parallel manipulator is computed as the center of mass of all of: the mobile platform (including all components fixed to it such as sensors, fixtures, etc.), the at least one movable device and the load.

This control of the position of the overall CoM plays a fundamental role in keeping cable tensions into prescribed admissible bounds. Indeed, 3rd Newton's law applied at the

level of the mobile platform states that the tensions from the cables need to balance the effect of any external wrench on the one hand, and of gravity on the other hand.

In some embodiments the instruction to move the movable device generates a movement in the movable device that is redundant with at least one degree of freedom of a set of controlled degrees of freedom of the mobile platform controlled by the cable system.

In particular, the fact that the movement of the movable device is redundant with the controlled movement of the mobile platform means that the overall CoM is displaced along the same DOFs as the ones the mobile platform is moved on using the cable system. This feature allows transferring tension to or from a set of actuators (to which a first set of cables is attached to) which have a tension that is reaching the higher or lower limit, to another set of actuators (to which a second set of cables is attached to) which have a tension that is well away from the bounds. If the movement of the CoM is not redundant with the controlled DOFs of the mobile platform, the displacement of the CoM has no effect on the forces in the actuators of the cable system. So, by making the movement of the movable device redundant with the controlled movement of the mobile platform, the tensions in all sets of cables are as far as possible from the limits: by moving the CoM, the distribution of the tensions in the cables changes, so as to keep the tension in the set of cables away from the limits.

As explained in the previous section, in the state of the art the only variable that can be changed is the tension in the cables. External, dynamics-induced or task-related wrenches are set by the requirements. Gravity acts on the weight of the mobile platform, the load and any other device on-board the mobile platform: this is a force located at the overall CoM and the moment of this force is dependent on the overall CoM location. Hence, the gravity wrench depends on the overall mass and the position of the overall CoM. The control of the position of the overall CoM by instructing the at least one movable device to move thus increases the wrench capabilities of the cable-driven parallel manipulator and, thereby, increases its capabilities of handling heavy loads and/or of tolerating large ranges of possible postures of a mechanical manipulator placed on-board its mobile platform beyond the capabilities of state of art cable-driven parallel manipulators. For a given overall mass, the set of locations of the overall CoM which corresponds to feasible wrenches (i.e. to admissible cable tensions) for a fixed external wrench form a bounded region space. In the present document, this predetermined region of space is referred to as the *CoM feasible region*. The weight of system composed of the mobile platform, the load, and any other devices placed on-board the mobile platform generates a wrench which, combined with the external forces is feasible (i.e. can be counteracted by the sum of forces from the cables within admissible values) if and only if the overall CoM lies inside the CoM feasible region.

The instruction to move is preferably triggered to compensate for some unbalance at

the mobile platform. This unbalance may be interpreted by having an external wrench acting on the mobile platform that when summed up with gravity wrench results in an overall wrench that is outside the feasible wrench set (which is the set of wrenches for which there is at least one set of cable forces to compensate this wrench without a cable going slack or exceeding its maximum tension). This unbalance may be due to several causes, such as displacement of the mobile platform, handling of the load, external action (such as wind), etc. and this unbalance can either be directly or indirectly measured (using sensors such as accelerometers, force sensors, etc.), or it can be anticipated and decided by means of a model and planning strategy of the whole cable-driven parallel manipulator. In the specific case of quasi-static operation, only gravity, applied at the overall CoM, applies: unbalance is understood as the overall CoM being outside or having the tendency to leave the CoM feasible region where the cable tensions are admissible, said region being linked to the feasible wrench set.

The at least one movable device is thus used to balance or modify the forces and moments (wrenches) due to the statics and dynamics of the mobile platform and its load, and external forces and moments on either of those, in order to keep the cable tensions within admissible bounds. Thereby, the use of at least one movable device mounted on the mobile platform of the cable-driven parallel manipulator increases the load capabilities and the usable volume of the workspace of the manipulator.

Moreover, the cable-driven parallel manipulator as just defined, which provides control over the overall CoM by means of the at least one movable device, enables the use of a high dexterity and small workspace system (such as a robotic arm) within a large workspace provided by a low dexterity system (the cable-driven parallel manipulator), thereby maximizing the possible postures and motions of the high dexterity and small workspace system. Indeed, the high dexterity system being placed on-board the cable-driven parallel manipulator mobile platform, the control over the overall CoM allows the cables to keep admissible tensions for a significantly larger set of possible postures and motions of the high dexterity system. This way, the operational capabilities of the cable-driven parallel manipulator can be expanded towards more complex tasks in terms of dexterity and reachable volume of operation.

In fact, in some embodiments of the present invention, the cable-driven parallel manipulator further comprises such an embarked manipulator (such as a robotic arm or any other multi degree-of-freedom manipulator) secured to the mobile platform. In this case, the control module is further configured to generate the instruction such that, upon moving the at least one movable device, any force and/or moment (wrench) exerted by the embarked manipulator is counteracted, at least partially, but in all cases such that the corresponding

wrench remains feasible; so, any wrench exerted by the embarked manipulator is counteracted by displacing the overall CoM to be within the predetermined region related to the embarked manipulator wrench.

In this case of the cable-driven parallel manipulator having a manipulator embarked on its mobile platform (such as the robotic arm), the use of the at least one movable device on-board the mobile platform, allows:

- The cable-driven parallel manipulator not to be necessarily oversized with respect to the embarked manipulator, and/or

- The postures and motions of the embarked manipulator not to be strongly restricted.

In embodiments comprising the embarked manipulator, which is usually controlled by a controller (usually encased in some sort of cabinet or box), the at least one movable device comprises such controller cabinet or part of it. Thereby, there is no need to add any additional element or mass in the cable-driven parallel manipulator platform: the controller of the embarked manipulator is made movable and made part of the at least one movable device.

The at least one movable device is controlled in function of actualized data sent by the control unit of the cable system related to the current mobile platform wrench and/or current cable tensions. This data link existing between the control module of the movable device and the control unit of the cable system (which can be wireless) is important to ensure the consistency of, on the one hand, the motions of mobile parts of the at least one movable device and, on the other hand, the evolution in time of the mobile platform wrench and/or cable tensions.

Data transferred through this data link (which can also be synchronized) can be (but are not limited to) the position of the at least one movable device, the orientation of the cables with respect to the mobile platform, the force value and direction generated by each cable on the mobile platform, or an estimation of the wrench applied on the mobile platform. In another embodiment, data input from a set of sensors, such as (but not limited to) accelerometers, force sensors, are used to estimate the wrench at the mobile platform.

This synchronized data link allows the actual motion of the overall system to be close to the desired motion, the latter being planned so as to ensure the feasibility of the platform wrench. An example of planning consists in keeping the sum of the external wrench and the gravity wrench corresponding to the desired motion as far away as possible from the borders of the feasible wrench set, which corresponds to the most resilient situation against unplanned wrenches.

Depending on the application of the cable-driven parallel manipulator, and its foreseen movements, the at least one movable device can be differently moved. Each of these possible motion combinations can be advantageous according to the actual implementation

of the present invention:

The at least one movable device preferably has at least one degree of freedom. In some embodiments, this at least one degree of freedom is redundant with at least one degree of freedom of a set of degrees of freedom of the mobile platform controlled by the cable system.

The at least one movable device may be movable along three mutually orthogonal directions; or along two directions and also rotatable at least around one direction; or along one direction and also rotatable around two directions; or movable along one translation direction and also rotatable around one rotation direction, the translation and rotation directions being orthogonal; or rotatable around two orthogonal directions. All these arrangements allow a positioning along three translational directions of space of a counterweight device, placed at the tip of the movable device, possibly with some coupling; the three translational directions, or the spherical coordinates in the case of the two orthogonal rotations, allowing to generate a displacement of the center of mass of all of the mobile platform, the at least one movable device and the load.

The at least one movable device can comprise one or more tanks mounted or placed on the mobile platform, and means for pumping liquid in such tank(s); in this embodiment, the control module generates an instruction to pump liquid in one or more of the tanks, so as to displace the overall CoM in at least one direction.

In some embodiments the mobile platform remains substantially vertical, and the at least one movable device may be movable along two horizontal orthogonal directions; or along one horizontal direction and also rotatable around one vertical direction. This arrangement takes the advantage of the gravity force being always vertical; therefore, any translational movement of the at least one movable device along a vertical direction is not useful and can be discarded in this particular embodiment.

In some embodiments the mobile platform is tilted around substantially only one of the originally horizontal axes of its own reference frame, and the at least one movable device may be movable along one horizontal direction normal to the originally horizontal axis of tilting, or rotatable around a revolution axis parallel to the originally horizontal axis of tilting of the movable platform. This specific arrangement can deal with any moment generated by gravity on a load attached to the mobile platform at a vertical distance from the geometric center of the platform because of the tilting.

Movement of the at least one movable device along the surface of a sphere may actually be enough for specific cases (off-centered load picking, for instance, with tilting of the platform implied).

If a manipulator is placed on-board the mobile platform of the cable-driven parallel

manipulator, some of the previously mentioned degrees of freedom of the at least one movable device can be shared with the degrees of freedom of the on-board manipulator, leaving at least one own degree of freedom for the at least one movable device. In the specific situation of the unbalance being due to the movements or the position of the links of the embarked manipulators, the unbalance is mostly related to the degrees of freedom of the embarked manipulator. Sharing the degrees of freedom between the manipulator and the at least one movable device reduces the number of degrees of freedom to build in the whole system while keeping the capability of the system to balance the wrenches applied by the on-board manipulator on the mobile platform of the cable-driven parallel manipulator.

Another aspect of the invention relates to a method for stabilizing a load of a cable-driven parallel manipulator, the cable-driven manipulator comprising a mobile platform connected to a cable system whereto the load is attachable and a movable device mounted on the mobile platform; the method comprising:

- computing an overall center of mass of the cable-driven parallel manipulator as the center of mass all of: the mobile platform, the at least one movable device and the load; and
- generating an instruction to move the movable device for displacing the overall center of mass to be within a predetermined region.

The predetermined region is a stability region which can be computed as the CoM feasible region, which comprises a set of locations of the overall center of mass which corresponds to feasible wrenches.

The method preferably further comprises:

- computing external wrenches and gravity wrenches exerted on the mobile platform;
- generating an instruction to move the at least one movable device for displacing the overall CoM so that the overall center of mass stays inside the predetermined region (which preferably is the CoM feasible region) related to the computed external wrench.

As previously explained, the control of the at least one movable device mounted on the mobile platform can increase performance of the cable-driven parallel manipulator, such as the usable workspace and the load capabilities of the manipulator.

In fact, the control of the movement of the at least one movable device mounted on the mobile platform has an effect on the distribution of the tensions in the cables of the cable-driven parallel manipulator. Performance such as stability is directly linked to the tensions in the cables. Thus, the proposed method can therefore be seen as a way to optimize the tensions in the cables in view of optimizing performance of the cable-driven parallel manipulator through the movement of the at least one movable device.

In some embodiments the instruction to move the movable device generates a movement in the movable device that is redundant with at least one degree of freedom of a

set of degrees of freedom of the mobile platform controlled by the cable system.

The method preferably comprises embarking a manipulator on-board the mobile platform of the cable-driven parallel manipulator. In this case, the instruction to move the at least one movable device also counteracts any force and/or moments exerted by the embarked manipulator.

In some embodiments, the method further comprises establishing a data link between a control unit of the cable system and a control module of the at least one movable device so that movements/ operations of the cable system and of the at least one movable device are shared (preferably synchronized) to prevent any cable of the cable system from being slack or from having a tension larger than a prescribed maximum admissible tension.

If an embarked manipulator is included, synchronization with the movements/ operations of the embarked manipulator is also comprised.

The different aspects and embodiments of the invention defined in the foregoing can be combined with one another, as long as they are compatible with each other.

Additional advantages and features of the invention will become apparent from the detailed description that follows and will be particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

To complete the description and in order to provide for a better understanding of the invention, a set of drawings is provided. Said drawings form an integral part of the description and illustrate an embodiment of the invention, which should not be interpreted as restricting the scope of the invention, but just as an example of how the invention can be carried out. The drawings comprise the following figures:

Figure 1 is a schematic perspective view of a cable-driven parallel manipulator with a conventional robotic arm placed on-board the mobile platform.

Figure 2 is a schematic perspective view of a cable-driven parallel manipulator in accordance with an exemplary embodiment of the present invention.

Figure 3 is a schematic perspective view of a cable-driven parallel manipulator in accordance with another exemplary embodiment of the present invention.

Figure 4 is a schematic representation in the Mx-My moments plane, showing a graph which coordinates are moments around X and Y, showing how the cable-driven parallel manipulator can handle external wrenches beyond its achievable wrench region. It pictures the way the CoM feasible region is calculated from the external and gravity wrenches.

DESCRIPTION OF A WAY OF CARRYING OUT THE INVENTION

The following description is not to be taken in a limiting sense but is given solely for

the purpose of describing the broad principles of the invention. Embodiments of the invention will be now described by way of examples, with reference to the above-mentioned drawings showing elements and results according to the invention.

As previously indicated, Figure 1 shows a cable-driven parallel manipulator 1 with a conventional robotic arm 2 mounted on its mobile platform 3; the mobile platform is sustained by a set of cables 4, operated by corresponding winches (not shown in the Figure).

Figure 2 shows a first implementation of a cable-driven parallel manipulator 10 having a mobile platform 20 connected to a plurality of cables 30. The effect of controlling the lengths of the cables 30 is to have a control on the six degrees of freedom of the platform. A robotic arm 40 with six degrees of freedom is bolted downwards below the mobile platform 20 of the cable-driven parallel manipulator.

As shown in Figure 2, the cable-driven manipulator further comprises a balancing mechanism 50 (movable device). The mobile platform 20 of the cable-driven manipulator 10 is used in a substantially constant orientation, which means that the capabilities of the cable-driven parallel manipulator to generate rotations is only used to withstand moments. As a result, the balancing mechanism 50 only needs two degrees of freedom to prevent any cable of the cable system from being slack or from having a tension larger than a prescribed maximum admissible tension. Considering that the cable system allows controlling the position of the platform on all six degrees of freedom of space, the movement generated on said balancing mechanism 50 is redundant with at least one degree of freedom of the mobile platform 20 controlled by the cable system.

Following the usual construction of robotic arms in the market, the robotic arm 40 is featured with the following six revolute joints: firstly, a “vertical” revolute joint; then, two “horizontal” revolute joints with parallel rotation axes and separated by a first link; fourth, a revolute joint in line with the second link, and finally two revolute joints; the three last revolute joint axes intersect at the robot wrist center point.

Because of this construction, the center of mass of the robotic arm is situated on, or close to, a plane normal to the second and third revolute joint axes. This plane rotates with the first joint. As a result, full, or efficient, balancing of the position of the center of mass of the robotic arm can be achieved by moving the center of mass of the movable device 50 in this same plane. In the present embodiment, this is achieved with the movable device 50 being movable on the axis that is the intersection of this same plane and a horizontal plane; this movement is materialized here by a set of sliders 51 that are fixed to the portion of the robotic arm 40 located between the first and the second joints, and a lead screw and nut mechanism driven by a motor for actuation. The first joint of the robotic arm can therefore be considered as one of the joints of the movable device 50. The movable device 50 is moved

in unison with the robotic arm 40 to keep it balanced at all times, and can be implemented as a complementary system to the robotic arm.

In this particular implementation, the movable device 50 includes a movable mass 52, which is the electrical equipment used for driving and controlling the robotic arm 40, which can be composed by but not limited to the controller cubicle containing the electronic drives of the various motors. Electrical wiring from the mobile platform to the cubicle and thereafter from the cubicle to the motors of the movable device and the robotic arm is achieved using cable carrier chains.

Once the robotic arm is operating over a specific load, its center of mass is typically situated at a fixed distance from the wrist point, and it cannot be completely balanced by the movable device 50. This is not considered critical as the unbalance provided by the load off the plane of the robotic arm or the dynamics of the wrist axes is limited by the moment capability of said wrist axes of the robotic arm, which is typically lower than the moment capability of the cable-driven parallel manipulator.

Figure 3 shows a second implementation of the invention. In this case, the mobile platform 20 is held by the same arrangement of cables 30 providing control on its six degrees of freedom. It is equipped with a robotic arm 40' having seven degrees of freedom. The controller of the robot arm is integrated inside the base of the arm. The cable-driven manipulator can be used in any rotational position, and it is thus provided with a movable device 50' with three degrees of freedom to fully counteract the forces and moments generated by the robotic arm 40'. In this case, the movable device 50' is built using three sliders 51' oriented in mutually orthogonal directions and actuated by the corresponding electric motors. The terminal movable mass 52' of the movable device 50' can therefore be positioned in any position to counteract the moment from the robotic arm 40'. Considering that the cable system allows controlling the position of the platform on all six degrees of freedom of space, the movement of said balancing mechanism 50' is redundant with at least one controlled degree of freedom of the mobile platform 20.

As previously explained, for a given pose of a specific cable-driven parallel manipulator, the feasible wrench set is the set of mobile platform wrenches (forces and moments) which the cable system can counteract, such that the tension in each cable of the cable system remains within prescribed admissible bounds.

The feasible wrench set 100 of the cable-driven parallel manipulator is represented in Figure 4 in the Mx-My moment plane, i.e., the plane whose x-axis and y-axis represent the moments around the horizontal axes X and Y (Mx and My), respectively. This 2-dimensional planar representation is a simplification of the actual feasible wrench set which is a 6-dimensional object, this simplification aiming at easing its representation. Besides, moments

around X and Y (horizontal axes) can be generated by a horizontal displacement of the overall CoM of the at least one movable device. The point C of the feasible wrench shown in Fig. 4 is set as the point where the moments Mx and My are equal to 0. Region 100 also corresponds to the feasible wrench set of the equivalent state of the art cable-driven parallel manipulator. No wrench outside region 100 can be balanced by said manipulator by just acting on the forces in the cables, as it is done in existing cable-driven parallel manipulators.

A nominal wrench is introduced: it is the wrench that the cable tensions have to counteract when the at least one movable device is at a neutral position, meaning that the at least one movable device does not generate any moment around X and Y. The nominal wrench can be the external wrench as defined above, or an off-centered load, or the actions of an on-board robotic arm (such as but not limited to the moments and forces due to a posture in quasi-static case), or the sum of those actions. Region 101 is the set of wrenches equal to the sum of the nominal wrench and the possible wrenches generated by the at least one movable device in all of the possible coordinate sets for the overall CoM. Each point in region 101 is therefore linked to a coordinate set of the at least one movable device.

Region 102 is introduced: it is the intersection between region 100 and 101. Being part of 100, any wrench within this region belongs to the feasible wrench set. On the other hand, being part of region 101, region 102 may be associated with a region of space for the overall CoM. This region of space associated with region 102 is the CoM feasible region. As a result, with the overall CoM inside this CoM feasible region, there exist a set of admissible cable tensions for which the sum of the wrench from the cables, the wrench from the action of gravity and the nominal wrench equals to zero. If there is no intersection between region 100 and 101, it means that the nominal wrench considered cannot be balanced by the proposed cable-driven parallel manipulator.

Figure 4 therefore shows that it is possible with the disclosed invention to increase the load, in particular with respect to moments around X and Y using gravity. It is also possible to increase the load in the other wrench directions (Fx, Fy, Fz, Tz) using the dynamics of the movable device. Therefore, the capabilities of the cable-driven parallel manipulator are increased, since wrenches beyond the original feasible wrench set (equivalent to the feasible wrench set of a state of the art cable-driven parallel manipulator) can be balanced with this method. It is also possible to choose the best wrench point in region 102 with regard to the performance index of the cable-driven parallel manipulator, for instance, through mapping a performance index over the region 102 and choosing the best wrench point.

In fact, the displacement of the overall CoM by the means of the balancing mechanism creates a shift in the 6D space of the wrench components, said shift direction and amplitude being a function of the actual displacement of the overall CoM by means of the at least one

movable device: for a calculated wrench applied at the mobile platform, a region for positioning of the center of mass of all of the mobile platform, the at least one movable device and the load can be determined. The ability of moving the overall center of mass therefore allows wrenches that were not originally in the feasible wrench set to be counterbalanced. Said wrenches could be originated by:

- The picking of a load whose center of mass is not vertically aligned with the geometric center point, generating a moment,
- The tilting of a load around horizontal axis whose center of mass is situated at rest at a vertical distance from the geometric center point,
- The forces generated by devices on-board the movable platform, such as a manipulation device for holding the load,
- External forces and moments due to interaction between the movable platform or a manipulation device secured on the movable platform and the environment.

The two embodiments shown in Figures 2 and 3 reflect a cable-driven parallel manipulator with an embarked manipulator 40, 40'. However, when the cable-driven parallel manipulator is not equipped with on-board devices that provide additional local dexterity, the cable tensions still depend highly on the location of the overall CoM of the set consisting of the mobile platform and its load. In various situations, the load may be off-centered or its mass distribution may not be uniform. Therefore, to be able to handle a variety of loads with cable tensions remaining into admissible bounds, especially in contexts where the load cannot be placed appropriately with respect to the mobile platform, the position of the overall CoM may have to be modified in order to keep the cable tensions into admissible bounds, which in the present invention is possible by means of the balancing mechanism 50, 50'.

In this text, the term "comprises" and its derivations (such as "comprising", etc.) should not be understood in an excluding sense, that is, these terms should not be interpreted as excluding the possibility that what is described and defined may include further elements, steps, etc.

The invention is obviously not limited to the specific embodiment(s) described herein, but also encompasses any variations that may be considered by any person skilled in the art (for example, as regards the choice of materials, dimensions, components, configuration, etc.), within the general scope of the invention as defined in the claims.

CLAIMS

1. Cable-driven parallel manipulator (10) comprising:
- a support structure;
- a cable system (30) mounted on the support structure; and
- a mobile platform (20) connected to the cable system (30) whereto a load is attachable;
- the cable system being controlled by a control unit to position and orientate the mobile platform (20) and/or to apply forces and/or moments on the mobile platform (20);
characterized in that the cable-driven parallel manipulator further comprises:
- at least one movable device (50, 51, 52, 50', 51', 52') mounted on the mobile platform (20);
- a control module configured to generate an instruction to move the movable device (50, 51, 52, 50', 51', 52') for displacing an overall center of mass of all of: the mobile platform (20), the at least one movable device (50, 51, 52, 50', 51', 52') and the load, such that, upon moving the movable device (50, 51, 52, 50', 51', 52'), the overall center of mass is within a predetermined region (101).

2. Cable-driven parallel manipulator (10) according to claim 1, wherein the instruction to move the movable device (50, 51, 52, 50', 51', 52') generates a movement in the movable device that is redundant with at least one degree of freedom of a set of degrees of freedom of the mobile platform (20) controlled by the cable system (30).

3. Cable-driven parallel manipulator (10) according to any of claims 1-2, wherein the mobile platform further comprises an embarked manipulator (40, 40') secured to the mobile platform (20).

4. Cable-driven parallel manipulator (10) according to claim 3, wherein the control module is configured to generate the instruction such that, upon moving the movable device (50, 51, 52, 50', 51', 52'), any force and/or moment exerted by the embarked manipulator (40, 40') is counteracted by displacing the overall center of mass to be within the predetermined region (101).

5. Cable-driven parallel manipulator (10) according to any of claims 1-4, further comprising a data link between the control unit of the cable system (30) and the control module of the movable device (50, 51, 52, 50', 51', 52'), the control module of the at least

one movable device being configured to take actualized data from the control unit of the cable system as an input.

6. Cable-driven parallel manipulator (10) according to any of claims 3-5, wherein the embarked manipulator (40, 40´) has shared degrees of freedom with the at least one movable device (50, 51, 52, 50', 51', 52').

7. Cable-driven parallel manipulator (10) according to any of claims 1-6, wherein the at least one movable device (50, 51, 52, 50', 51', 52') is movable along three mutually orthogonal directions; or along two directions and also rotatable at least around one direction; or along one translation direction and also rotatable around two directions; or along one translation direction and also rotatable around one rotation direction, the translation and rotation directions being orthogonal.

8. Cable-driven parallel manipulator (10) according to any of claims 1-7, wherein the at least one movable device (50, 51, 52, 50', 51', 52'), comprises one or more tanks in which a fluid can be pumped in and out.

9. Cable-driven parallel manipulator (10) according to any of claims 3-8, wherein the movable device (50, 51, 52) comprises a controller cabinet (52) of the embarked manipulator (40).

10. Method for stabilizing a load of a cable-driven parallel manipulator (10), the cable-driven parallel manipulator comprising a mobile platform (20) connected to a cable system (30) whereto the load is attachable, the cable-driven parallel manipulator further comprising a movable device (50, 51, 52, 50', 51', 52') mounted on the mobile platform (20);
the method comprising:
- computing an overall center of mass of the cable-driven parallel manipulator as the center of mass all of: the mobile platform, the at least one movable device and the load;
- generating an instruction to move the movable device (50, 51, 52, 50', 51', 52') for displacing the overall center of mass to be within a predetermined region (101).

11. Method according to claim 10, which preferably further comprises:
- computing external wrenches and gravity wrenches exerted on the mobile platform (20);
- generating an instruction to move the at least one movable device for displacing the

overall center of mass such that is stays inside the predetermined region (101) related to the computed external wrench.

12. Method according to any of claims 10-11, wherein the instruction to move the movable device (50, 51, 52, 50', 51', 52') generates a movement in the movable device that is redundant with at least one degree of freedom of a set of degrees of freedom of the mobile platform (20) controlled by the cable system (30).

13. The method of any of claims 10-12, in which the cable-driven parallel manipulator comprises an embarked manipulator (40, 40') to the mobile platform (20), wherein the step of generating an instruction to move the movable device comprises counteracting any force and/or moment exerted by the embarked manipulator (40').

14. The method of any of claims 10-13, in which the step of generating an instruction to move the movable device comprises inputting into a control module of the movable device updated data provided by a control unit of the cable system so as to compute the predetermined region.

15. The method of claim 14 when dependent on claim 13, which further comprises inputting into a control module of the movable device updated data provided by the embarked manipulator (40).

16. The method of any of claims 10-15, in which the step of generating an instruction to move the movable device comprises previously receiving data from sensors measuring any unbalance in the cable-driven parallel manipulator so as to compute the predetermined region.

17. The cable-driven parallel manipulator (10) of any of claims 1-9 or the method of any of claims 10-16, wherein the predetermined region is a stability region computed as the center of mass CoM feasible region, which comprises a set of locations of the overall center of mass which corresponds to feasible wrenches.

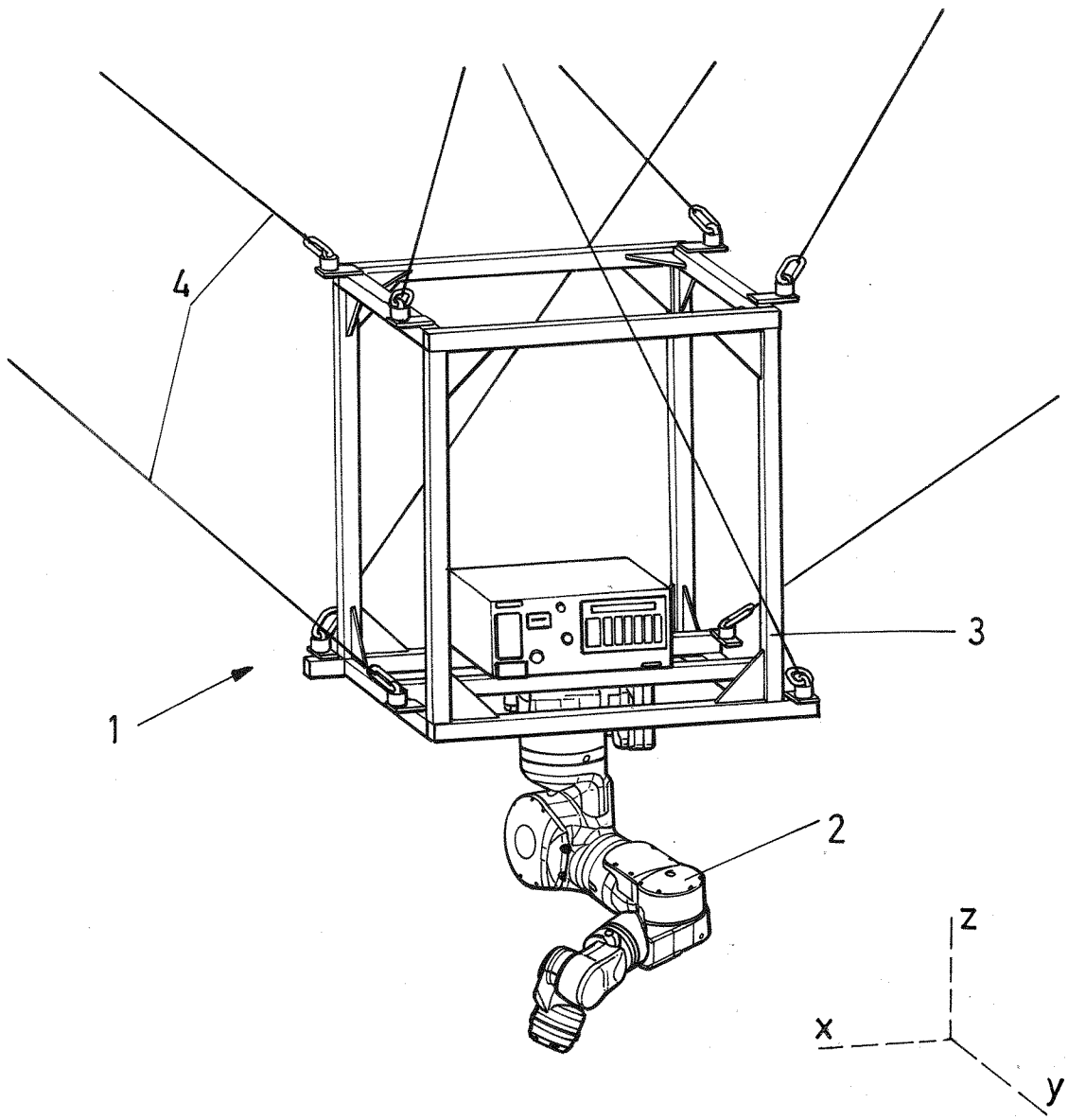

FIG.1

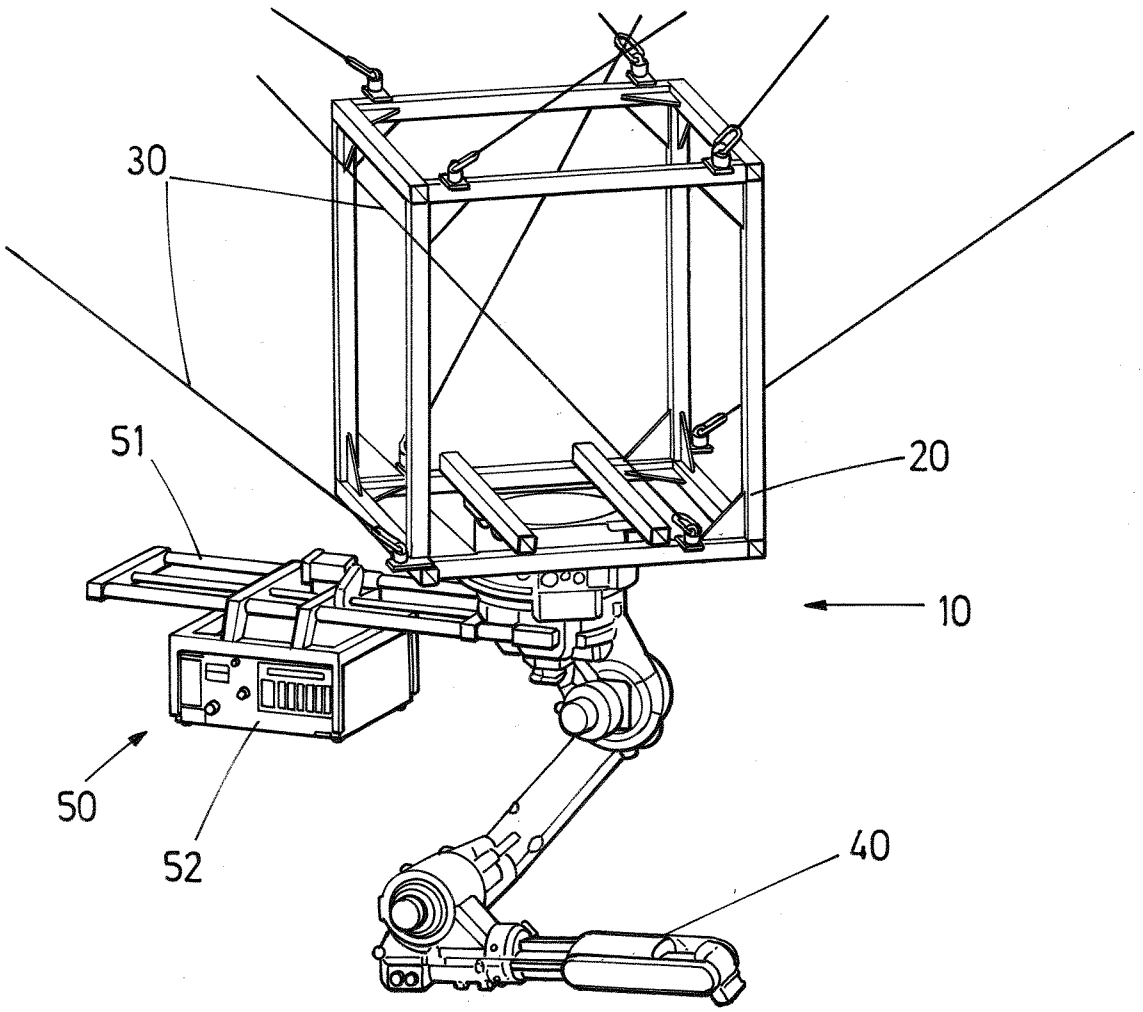

FIG.2

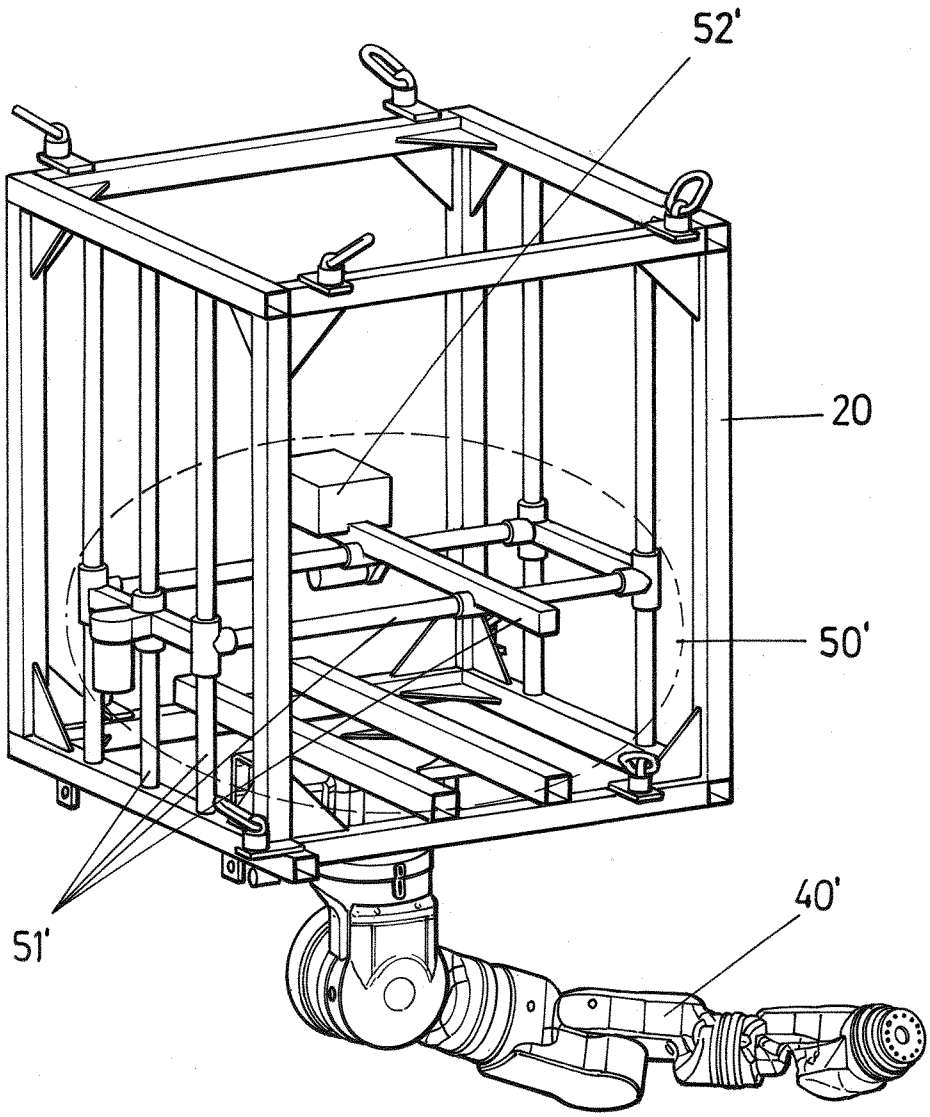

FIG.3

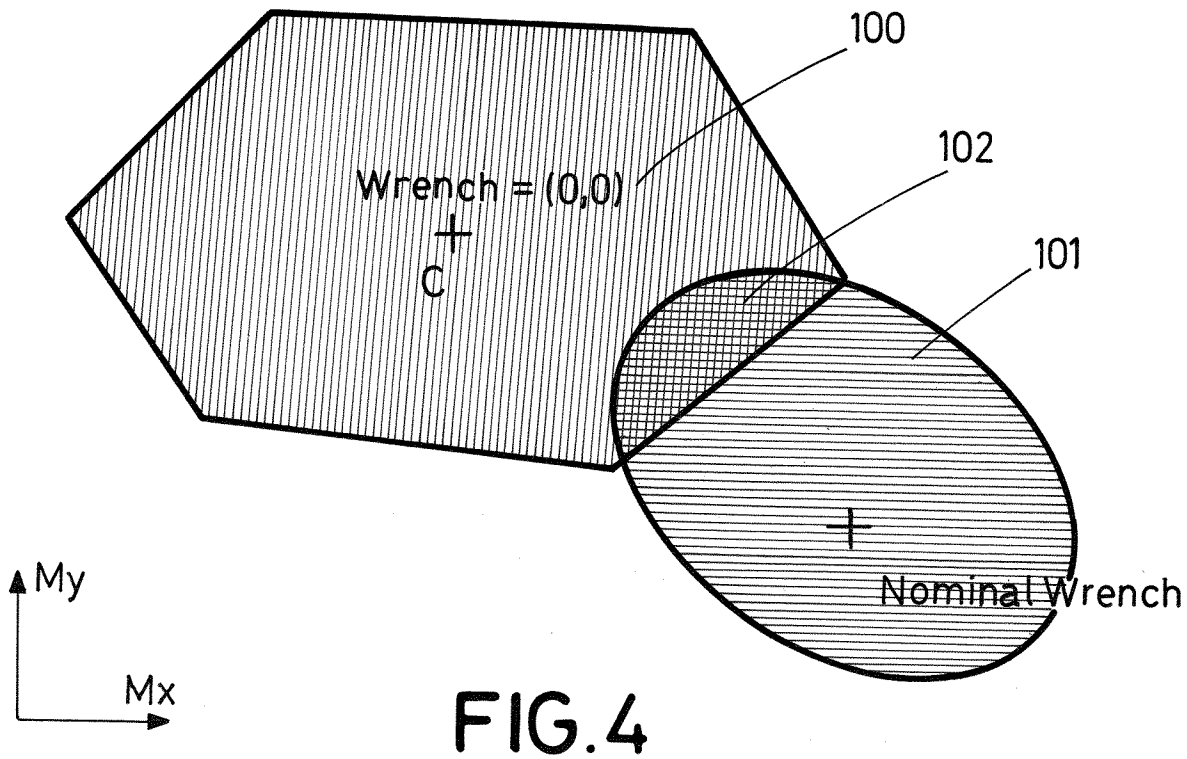

FIG.4

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/078504

A. CLASSIFICATION OF SUBJECT MATTER
INV. B25J9/00 B25J19/00
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 B66C

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, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	abstract; figures 1,1D,1E,1H	6,7,
	paragraphs [0080], [0082], [0086]	10-13
A	paragraphs [0122], [0123]	14-17

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Y	US 2011/071677 A1 (STILMAN MICHAEL [US]) 24 March 2011 (2011-03-24) abstract; figures 1,3,4,9 paragraph [0028] - paragraph [0032] paragraphs [0055], [0056] paragraph [0068] - paragraph [0071]	10-13

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
11 January 2018	26/01/2018

Name and mailing address of the ISA/	Authorized officer
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Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/078504

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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