

LIFTING DEVICE, LIFTING SYSTEM AND METHOD OF LIFTING A LOAD**TECHNICAL FIELD**

[0001] This application relates to the field of hoisting or lifting operations, and more particularly to a lifting device, a lifting system and a method of lifting a load.

BACKGROUND

[0002] Conventional hoisting/lifting operations, for example in Pre-fabricated, Pre-finished Volumetric Construction ("PPVC") and in precast constructions, are often presented with challenges relating to precision, productivity and costs. Preliminary findings show that the bulk of the time in hoisting operations is in trying to place or to fit a load into a predetermined position/placement. This increases the time required for on-site positioning and assembly of the load, adversely affecting the productivity of the operation and elevating building costs.

SUMMARY

[0003] According to an aspect, disclosed herein a lifting device. The lifting device comprises a frame couplable to a support; a plurality of wire rope systems coupled to the frame, the plurality of wire rope systems being configured to hold a load relative to the frame, wherein each of the plurality of wire rope systems comprises a wire rope with an independently adjustable operating length; and a plurality of sensors coupled to the frame, the plurality of sensors being configured to sense at least one parameter of the load.

[0004] In various embodiments, the lifting device further comprises a mass moveably coupled to the frame, wherein responsive to moving the mass relative the frame, a center of gravity of the frame is displaced to tilt the frame.

[0005] In various embodiments, the lifting device further comprises at least one flywheel gyroscope system coupled to the frame, each of the at least one flywheel gyroscope system being configured to provide a controllable torque to the frame.

[0006] According to another aspect, disclosed herein a lifting system. The lifting system comprises the lifting device of the above; and a controller in signal communication with the lifting device, the controller being configured to control the lifting device to independently vary each of three translational degrees of freedom and each of three rotational degrees of freedom of the load.

[0007] According to yet another aspect, a method of lifting a load is disclosed. The method comprises holding a load relative to a frame with a plurality of wire rope systems, the frame coupled to a support, wherein each of the plurality of wire rope systems comprises a wire rope with an independently adjustable operating length; receiving inputs from a plurality of sensors coupled to the frame, the plurality of sensors being configured to sense at least one parameter of the load; and based on the inputs from the plurality of sensors, independently adjusting the operating length of each of the wire rope.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Various embodiments of the present disclosure are described below with reference to the following drawings:

[0009] FIG. 1 is a perspective diagram of a lifting system according to various embodiments;

[0010] FIG. 2 is another perspective diagram of a lifting system according to various embodiments;

[0011] FIGs. 3A and 3B are frontal views of a lifting device levelling a load according to various embodiments;

- [0012] FIGs. 4A and 4B are lateral views of a lifting device levelling a load and displacing a load vertically according to various embodiments;
- [0013] FIGs. 5A and 5B are lateral views of a lifting device displacing a load laterally according to various embodiments;
- [0014] FIG. 6 is a lateral view of a lifting device according to various embodiments;
- [0015] FIG. 7A is another lateral view of a lifting device according to various embodiments;
- [0016] FIG. 7B is the lifting device of FIG. 7A levelling a load;
- [0017] FIG. 7C is the lifting device of FIG. 7A displacing a load laterally;
- [0018] FIG. 8 is a top view of a lifting device with a moving mass according to various embodiments;
- [0019] FIG. 9 is a schematic diagram of a flywheel gyroscope system according to various embodiments;
- [0020] FIG. 10 is a side view of FIG. 9;
- [0021] FIG. 11 is an illustration of the operation of a flywheel gyroscope system;
- [0022] FIG. 12A is a schematic diagram of a controller and a user controller according to various embodiments;
- [0023] FIG. 12B is a schematic diagram showing the server and client in the controller and user controller of FIG. 12A;
- [0024] FIG. 13 is an exemplary user interface of a user controller according to various embodiments;
- [0025] FIG. 14 is a flowchart of a control process according to various embodiments;
- [0026] FIG. 15 is a flowchart of a method of lifting a load according to various embodiments;
- [0027] FIG. 16 is a photo of an exemplary prototype lifting system;

[0028] FIGs. 17A and 17B show a prototype lifting system and corresponding structural dimensions;

[0029] FIGs. 18A and 18B show a prototype load and corresponding structural dimensions;

[0030] FIGs. 19A to 19D are simulations of a lifting system performing auto-levelling;

[0031] FIG. 20 is a sensor data plot of roll angle and pitch angle of a load during auto-levelling process;

[0032] FIG. 21 is a photo of an exemplary moving mass system of the prototype lifting system of FIG. 16;

[0033] FIG. 22 shows the results of lateral shifts in the load of FIG. 18A using the prototype lifting system of FIG. 16;

[0034] FIG. 23 shows an orientation measurement of the load of FIG. 18A which is being forcefully disturbed in multiple instances;

[0035] FIG. 24 shows an orientation response of active stabilization upon experiencing disturbance to the prototype lifting system of FIG. 16;

[0036] FIG. 25 shows the sensor data plot of load motions along the X-axis and Y-axis during motion adjustment;

[0037] FIG. 26 shows the sensor data plot of the roll angle, pitch angle, and yaw angle of the load of FIG. 18A during motion adjustment.

DETAILED DESCRIPTION

[0038] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as

described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0039] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0040] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance as generally understood in the relevant technical field, e.g., within 10% of the specified value.

[0041] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0042] As used herein, the terms “wire rope” may be used to refer to any one or more of the non-exhaustive examples such as “wire cable”, “loading cable”, “load cable”, “hoisting cable”, “loading rope”, “hoisting rope”, etc., as will be understood from the context. Therefore, “wire rope system” refers to a system with one or more wire ropes. The term “support” or “supporting point” may refer to a structure/device/module for holding and lifting the device, such as a crane hook, a crane, a hoisting hook, a hoisting crane, a supporting structure, a fixed crane, a crane truck or crane vehicle, a hoisting point on a vehicle, a hoisting point on an aerial vehicle, an aerial crane, etc.

[0043] The term “position” may generally refer to a location of an object. For example, a position of an object relative to a datum (or reference point) in three-dimensional (3D) space. In some examples, a position of an object may include a coordinate of the object in three-dimensional (3D) space, e.g. a coordinate (x1, y1, z1).

[0044] The term “orientation” may generally refer to a direction or a facing of an object. For example, an orientation of an object may include a reference point, a reference line or a reference surface of the object in relative to a datum in three-dimensional (3D) space. In various

examples, an orientation of an object may be quantified by a vector in 3D space, e.g. a unit vector $[x \ y \ z]$.

[0045] The terms “inclination” or “incline” may generally refer to a small downward movement or tilt of an object relative to the horizon. For example, the inclination may be a first rotation of an object about a first axis, a second rotation of the object about a second axis or a combination of both, wherein the first axis and second axis are parallel to the horizon.

[0046] Herein the term “controller” is used to refer generically to any device or component that can process such instructions and may include: a processor, a microprocessor, a processing unit, a plurality of processing elements, a microcontroller, a programmable logic device or any other type of computational device. That is, the controller may be provided by any suitable logic circuitry for receiving inputs, processing them in accordance with instructions stored in memory and generating outputs (for example to the memory components or on display). In this embodiment, the controller may be a single core or multi-core processor with memory addressable space. In one example, the controller may be multi-core, comprising—for example—an 8 core CPU. In another example, it could be a cluster of CPU cores operating in parallel to accelerate computations.

[0047] Hoisting or lifting operations in Pre-fabricated, Pre-finished Volumetric Construction (“PPVC”) and in precast constructions, are often presented with challenges relating to productivity and costs. In PPVC applications, challenges for PPVC on-site assembly includes the high cost of on-site assembly, the unavailability of cranes to assemble the modules and the low productivity of PPVC installation. For PPVC operations, the bulk of the operational time is used to fit the PPVC modular unit/component to a planned placement or location for precast module assembly and construction. Therefore, motivation stems from the advantages of precisely controlling, positioning and orientating of a load during PPVC on-site assembly.

[0048] Similarly, in other hoisting operations such as medical evacuation, quick and accurate placement of a load, such as a medical evacuation stretcher, avoids unnecessary delays/complications in rescue operations and saves time during emergencies. It may be appreciated that the application examples of the load as disclosed above are non-exhaustive and non-limiting.

[0049] The present invention provides a lifting system and a lifting device for reliable, safe, and efficient hoisting operation during load handling and placement. In addition to accurate placement during hoisting, the lifting system and device may stabilize a load during hoisting operations. As examples, the load may include containers/cargos, construction materials and precast modular components, including large PPVC modules or modular construction units, etc.

[0050] In various embodiments, the lifting system and device may independently adjust and/or stabilize each of the six degrees of freedom (DOF) of the load. In an example, the load may be a modular construction unit for PPVC. The six DOFs of the load may include three translational DOFs (3T) and three rotational DOFs (3R). The 3T may include (1) Moving up and down (elevating/heaving); (2) Moving left and right (strafing/swaying); (3) Moving forward and backward (walking/surging); and the 3R may include (4) Swivels left and right (yawing); (5) Tilts forward and backward (pitching); (6) Pivots side to side (rolling). Further, the lifting system and device may auto-level the load during operation, make lateral displacement/adjustment to the load for precise positioning, and stabilize the load during movement of the load.

[0051] To aid understanding and not to be limiting, various embodiments of a lifting system for lifting a load will be described below with reference to the appended figures. FIGs. 1 and 2 are perspective diagrams of a lifting system 50 and a lifting device 100 for lifting a load 60. The lifting system 50 includes a lifting device 100 in signal communication with a controller 400. In some embodiments, the controller 400 may be configured to control the lifting device

to independently vary each of three translational degrees of freedom (3T) and each of three rotational degrees of freedom (3R) of the load 60. In various embodiments, the controller 400 may be in a wireless signal communication with the lifting device 100. Further, the lifting system 50 may further include a user controller 405 disposed or located remotely from the controller 400. The user controller 405 may be in wireless signal communication with the controller 400. Therefore, the user or operator may be located away from the load/lifting system ensuring operator safety. The user controller 405 may be configured to transmit a control command from a user to the controller 400.

[0052] According to various embodiments, the lifting device 100 may include a frame 102 in a rectangular form. The frame 102 may be coupled or coupleable to a support 80 which provides a supporting/lifting force to the frame 102. In some embodiments, the support 80 may be a movable structure such that the frame 102 is displaceable by movement of the support 80. As examples, the support may include a crane hook or a mounting portion of a crane. The lifting device 100 may further include a plurality of wire rope systems 110 coupled to the frame. As shown in FIGs. 1 and 2, the lifting device 100 may include four wire rope systems 110a/110b/110c/110d. The wire rope systems 110a/110b/110c/110d may collectively hold the load 60 relative to the frame 102 and the support 80.

[0053] In other embodiments, the lifting system or lifting device may include other quantities of wire rope systems, such as two, three, five, six, eight, etc. In some embodiments, the number of wire rope systems may be determined based on a geometry of the load 60 or a number of supporting points on the load 60. In some embodiments, the frame 102 may generally be in a polygonal form. In some embodiments, the structure of the frame 102 may correspond to the number of wire rope systems. For example, the frame 102 may be in a triangular form corresponding to three wire rope systems; in a pentagonal form corresponding to five wire rope

systems; in a hexagonal form corresponding to five wire rope systems; and an octagonal form corresponding to eight wire rope systems.

[0054] In various embodiments, each of the wire rope system 110a/110b/110c/110d may include a wire rope 112a/112b/112c/112d. In various embodiments, each of the wire rope system 110a/110b/110c/110d may further include an electric winch 114a/114b/114c/114d which is coupled to the frame 102. The electric winches 114a/114b/114c/114d may be configured to independently adjust, for example, to pull on or to release, each of the wire rope 112a/112b/112c/112d to displace the load 60 relative to the frame 102. In some embodiments, one or more electric c 114a/114b/114c/114d may be coupled to and positioned at each corner of the frame 102.

[0055] In various embodiments, each wire rope 112a/112b/112c/112d may include an independently adjustable operating length (OL). The operating length (OL) of each wire rope 112a/112b/112c/112d may be defined by a length of the wire rope between the respective electric winches 114a/114b/114c/114d and the load 60. Therefore, adjusting each operating length changes a length of the respective wire rope between the frame 102 and the load 60. FIGs. 1 to 4B shows a variety of examples of operating length (OL) of the wire ropes 112a/112b/112c/112d. In some embodiments, each wire rope 112a/112b/112c/112d may have an operating length (OL) which is independently adjustable by the respective electric winches 114a/114b/114c/114d. In alternative embodiments, an actuatable spool or actuatable tensioning mechanism may be provided in place of each of the electric winches 114 for independently adjusting the respective operating lengths of the wire ropes 112.

[0056] In various embodiments, the lifting device 100 may include one or more moving mass 120 moveably coupled to the frame 102. The mass 120 may be movably coupled to a top surface 102a of the frame 102 or the top of the frame 102. For example, the mass 120 may be movably coupled to the top surface 102a via a linear stage, a track or a rail. Further, mass 120

may be displaceable or movable relative to the frame 102 using one or more actuators. Responsive to moving the mass 120 relative the frame 102, a center of gravity of the frame 102 may be displaced, tilting the frame 102 relative to the support 80.

[0057] In various embodiments, the lifting device 100 may further include one or more torque generating system 130 coupled to the frame 102. The torque generating system 130 may be coupled to a bottom surface 102b of the frame 102 or a bottom of the frame 102. The torque generating system may be coupled to a center of the bottom surface 102b. The torque generating system 130 may be configured to apply one or more torques collectively to the frame 102 and the load 60. For example, the torque(s) applied to the frame 102 and the load 60 may be about the gravity vector (GV). The torque generating system 130 may be flywheel gyroscope system or flywheel-based system. In some embodiments, each of the flywheel gyroscope system 130 may be configured to apply a controllable torque on the frame 102.

[0058] In various embodiments, the lifting device 100 may also include one or more sensors coupled to the frame 102. In various embodiments, one or more sensors may be detachably coupled to the load 60. The sensors may be configured to sense or to measure a parameter of the load 60 and/or a parameter of the frame 102. For example, the sensors may measure a position and/or an orientation of the load 60. In other examples, the sensors may measure a position and/or an orientation of the frame 102. In further examples, the sensors may measure a relative displacement, a relative velocity and/or a relative acceleration of the load 60 relative to the frame 102.

[0059] In various embodiments, the lifting device 100 may further include an inclinometer 140 removably coupled to the load 60. The inclinometer 140 may be coupled to a bottom of the load 60. The inclinometer 140 may be removable from the load 60 by various coupling means, such as a mechanical catch, a magnetic coupling, etc. The inclinometer 140 may be configured to determine an inclination of the load 60 relative to the support 80 or the ground. In some

embodiments, the inclinometer may be a 2D inclinometer configured to measure inclinations of the load 60 in two axes relative to the support 80 or ground. For example, the inclinometer 140 may be configured to measure a first inclination angle along a first axis 91 and to measure a second inclination angle along a second axis 93. The first axis 91 and the second axis 93 may be orthogonal to each other. The first axis 91 and the second axis 93 may also be orthogonal to the gravity direction or the third axis 95.

[0060] In various embodiments, the lifting device 100 may further include one or more imaging devices 150 such as cameras. In some embodiments as shown in FIGs. 1 and 2, the cameras 150a/150b/150c/150d may be coupled to respective sides of the frame 102. The cameras 150a/150b/150c/150d may also be orientated towards the load 60 to capture and provide a respective image of the load 60. For example, the images may include respective top views of the load 60 or a portion of the load 60. Further, the images may also include the surroundings of the load 60, such as the on-site PPVC construction.

[0061] In various embodiments, the lifting device 100 may further include one or more gyroscopic sensor(s) 160a coupled to the frame 102. Further, during the lifting operation, one or more gyroscopic sensor(s) 160b may also be coupled to the load 60. The gyroscopic sensor 160a may be configured to determine an orientation of the frame 102. The gyroscopic sensor 160b may also be configured to determine an orientation of the load 60. In some examples, the gyroscopic sensors 160a/160b may be fibre optics gyroscope sensors. It may be appreciated that other sensors or sensor implementations may be adapted for obtaining or determining other measurements, such as rotational parameters of the electric winch, tension measurements of the wire rope, inclination measurements of the load 60 and/or the frame 102, etc.

[0062] Referring to FIG. 2, the lifting system 50 and lifting device 100 may be configured such that each of the six DOFs (3T and 3R) of the load 60 may be independently controlled. For example, the three translational DOFs (3T) may include moving up and down

(elevating/heaving) along axis 95; moving left and right (strafing/swaying) along axis 93; and moving forward and backward (walking/surging) along axis 91. In addition, the three rotational DOFs (3R) may include rotating or swiveling 96 left and right (yaw) about axis 95; rotating or tilting 94 forward and backward (pitch) about axis 94; and pivoting 92 side to side (roll) about axis 91. In various embodiments, a combination of two or more of the six DOFs may be controlled together, either concurrently or sequentially.

[0063] In various embodiments, the controller 140 may control each of the electric winches 114a/114b/114c/114d to independently adjust each of the wire ropes 112a/112b/112c/112d to move the load 60 relative to the frame 102 or relative to the support 80. In some embodiments, the controller 140 may control each of the electric winches 114a/114b/114c/114d to independently adjust each of the wire ropes 112a/112b/112c/112d to level the load 60 relative to the support 80 or the horizon. In some embodiments, the controller 140 may control each of the electric winches 114a/114b/114c/114d responsive to inputs from one or more sensors, such as a position of the load 60 based on the cameras 150 or an inclination of the load 60 from the inclinometer 140.

[0064] The lifting system 50 and lifting device 100 of the present disclosure may be configured to perform auto-levelling of the load relative to the support or ground, making it suitable for the modular unit installation process. Apart from ensuring that the load is level during the hoisting process, the lifting system 50 and the lifting device 100 may keep the load level to the horizon during displacement, such as when the load is lowered or lifted into position. In addition, the controller 400 of the lifting system 400 may respond to shifts, tilts or offsets to the centre-of-gravity of the frame and/or the load, by making corresponding adjustments for yaw stabilization and lateral positioning.

[0065] FIG. 3A shows a frontal view of a lifting system 50/lifting device 100 lifting a load 60 according to various embodiments. Based on inputs from the sensors, such as the cameras

150 and the inclinometer 140, the controller 140 may control the electric winches 114a/114b/114c/114d to collectively displace the load 60 relative to the frame 102 along axis 95 (first translational DOF), from a first position 60a to a second position 60b. Further referring to FIG. 3B, based on inputs from the sensors, such as the cameras 150 and the inclinometer 140, the controller 140 may control the electric winches 114a/114b/114c/114d to rotate 92 the load 60 relative to the frame 102 (first rotational DOF), from a first position 60a to a second position 60b to level the load 60. Subsequently or concurrently, the controller 140 may control the electric winches 114a/114b/114c/114d to displace the load 60 along axis 95 from the second position 60b to a third position 60c.

[0066] FIG. 4A shows a lateral view of a lifting system 50/lifting device 100 lifting a load 60 according to various embodiments. Based on inputs from the sensors, such as the cameras 150 and the inclinometer 140, the controller 140 may control the electric winches 114a/114b/114c/114d to collectively displace the load 60 relative to the frame 102 along axis 95, from a first position 60a to a second position 60b. Further referring to FIG. 4B, based on inputs from the sensors, such as the cameras 150 and the inclinometer 140, the controller 140 may control the electric winches 114a/114b/114c/114d to rotate 94 the load 60 relative to the frame 102 (second rotational DOF), from a first position 60a to a second position 60b to level the load 60. Subsequently or concurrently, the controller 140 may control the electric winches 114a/114b/114c/114d to displace the load 60 along axis 95 from the second position 60b to a third position 60c. It may be appreciated that the displacement and levelling operations as described above and shown in FIGs. 3A to 4B, may be performed sequentially and/or concurrently or in a combination.

[0067] In various embodiments, for effective and accurate positioning, displacing or shifting of the load, the lifting system 50 and lifting device 100 may be configured to provide a precise and controlled lateral shift or lateral movement to the load 60 relative to the support 80. The

lateral shifting of the load 60 may be enabled by a combination of the moving mass 120 and the levelling operation performed by the electric winches 114 as disclosed in the previous section. Differentiating from a lateral shift due to the movement of the support 80, such as a crane movement, the lifting system 50 and lifting device 100 may laterally shift the load 60 by a relatively small displacement. Achieving such a small displacement may be challenging for conventional crane movements performed by the crane operator(s). In some examples, the lateral displacement may be up to 200 millimetres with a positioning resolution of 0.5 to 1 millimetres. In other words, the lifting system 50 allows fine lateral displacement to the load 60 by a minimum lateral displacement in the range of 0.5 to 1 millimetres. The lifting system 50 may also include a lateral displacement range from 0.5 to 1 millimetres up to 200 millimetres. The displacement range and positional resolution may depend on a weight of the moving mass 120 relative to the overall load 60. Further, the lateral shift provided by the lifting system 50 may be controllable and/or correctable, thus allowing any positioning error or excess lateral movements of the load 60 to be quickly corrected.

[0068] FIGs. 5A and 5B is a lateral view of a lifting system 50/lifting device 100 lifting and displacing a load 60 laterally according to various embodiments. FIG. 5A shows the lifting device 100 and the load in a neutral position supported by a support, such as a crane hook 80. In various embodiments, the crane hook 80 may include a plurality of crane cables or leg-chains 82 for holding the lifting device 100 and the load 60. For example, the crane hook 80 may include four leg chains 82 each coupled to a corner of the frame 203. In the absence of other external forces, the centre of gravity (CG) of the frame 102 and the load 60 combined, lies along a neutral line (NL). The neutral line (NL) may be formed by the crane hook 80 and the gravity vector (GV). In various embodiments, a moving mass system may be coupled to the frame 102. The moving mass system may include a moving mass 120 movably coupled to the frame 102. The moving mass 120 may move along a first direction 123. The displacement of the moving

mass 120 causes a shift in the CG of the frame 102 and the load 60, and the frame 102 to tilt 125. This results in the load 60 shifting and experiencing a change in inclination and/or orientation. Leveraging on this physical phenomenon, in synergy with the auto-levelling function as described previously, the lifting system 50/lifting device 100 performs a levelling operation on the load 60, such as controlling a pitch 94 and a roll 92 of the load 60 (FIG. 2), resulting in a lateral movement or lateral shift (LS) to the load 60 and the frame 102 relative to the support 80 along axis 91 (second translational DOF). This allows the lifting device 100 to controllably shift the load 60 laterally relative to a neutral position, alleviating the need for physically pushing and/or pulling the load 60 by human workers, providing a safe and accurate load placement during the last stage of PPVC on-site alignment and installation. It may be appreciated that a similar lateral shift of the load 60 may be performed along axis 93 (third translational DOF) by similar lateral shifting operations.

[0069] In various embodiments, the lifting system 50 / lifting device 100 may be configured with yaw stabilization and/or yaw control of the frame 102 and the load 60. In other words, the rotation 96 (FIG. 2) of the frame 102/load 60 about the axis 95 may be controlled, reduced or eliminated by the lifting system 50 (third rotational DOF). Yaw stabilization or control may be realised by the flywheel gyroscope system 130 as shown in FIG. 1 and 2. Based on the conservation of angular momentum and the effects of a “precessing” flywheel gyroscope or a flywheel gyroscope in precession, a controllable moment or torque about the axis 96 may be provided to the frame 102 and hence to the load 60 via the wire ropes 112. In other words, while a torque or moment is applied to the frame 102, based on the coupling of the load 60 via the wire ropes 112, the yaw of the load 60 is stabilized/controlled. By controlling each of the flywheel gyroscope system 130, the yaw of the lifting device 100 and the load 60 may be controlled and stabilized. In operation, the torque generated by the yaw stabilization may be used to counter external influences, such as wind and load yaw drift, and may be adapted to

cancel out or mitigate tendencies of rotational oscillation for the lifting device 100 and the load 60. In other examples, the yaw control may be performed to orientate the load 60 relative to a targeted position.

[0070] FIG. 6 illustrate an exemplary lifting system 50 and lifting device 100 according to various embodiments of the disclosure. The lifting device 100 may include a moving mass system 120, a flywheel gyroscope system 130, and an auto-levelling system (including 114 electric winches and 110 wire rope systems). The lifting device 100 may also include four sets of wire rope systems which may be pulley wire rope systems 110a/110b/110c/110d. Similar to previous embodiments, the wire ropes 112a/112b/112c/112d of the pulley wire rope systems 110a/110b/110c/110d may be independently adjusted and controlled by the respective electric winches 114a/114b/114c/114d.

[0071] In various embodiments, each pulley wire rope system 110a/110b/110c/110d may include respective pulley sets 116a/116c/116c/116d coupled to the frame 102. Further pulley sets 56a/56b/56c/56d may be provided coupled to the load 60. They pulley sets reduce the tension in the wire ropes 112a/112b/112c/112d and the required mechanical output from each electric winch. In various embodiments, each wire rope 112a/112b/112c/112d begins from a respective electric winch coupled to a corner of the frame 102, passes through multiple pulleys coupled to either the frame 102 or the load 60, and ends at a fixed coupling point 103 at the middle of the frame 102. Therefore, each wire rope 112a/112b/112c/112d has multiple coupling points (pulley) between the frame 102 and the load 60. The multiple coupling points increase robustness and safety during the lifting operation. The provision of the pulley sets distributes the weight of the load 60 using multiple pulleys, preventing the load 60 to be damaged due to large spans between lifting points as well as reducing the load on each of the electric winches 114a/114b/114c/114d.

[0072] FIG. 7A, 7B and 7C illustrate a lifting device with multiple pulley wire rope systems. In various embodiments, the lifting device 100 may include sensors such as rotational encoders 113, load sensors 118, and an inclinometer 140. In various embodiments, each of the rotational encoders 113a/113b/113c/113d may be mounted on a respective drum of each electric winch. This allows the rotational encoders 113 to provide precise signals corresponding to the rotation of the corresponding electric winch in real-time. In various embodiments, the load sensors 118a/118b/118c/118d may be coupled between the frame 102 and respective wire rope 112a/112b/112c/112d in series such that the load sensors 118a/118b/118c/118d may measure tension or any slack in the respective wire ropes 112a/112b/112c/112d in real-time.

[0073] In various embodiments, the inclinometer 140 may be coupled to the load, for example, coupled to the bottom or the top of a PPVC modular unit. The inclinometer 140 may sense/measure an inclination of the load 60. The inclinometer 140 may be a 2-axis inclinometer. Therefore, the inclination as measured may include a roll angle about axis 91 (FIG. 2) and a pitch angle about axis 93 (FIG. 2) of the load 60. The inclination measurement may be transmitted to the controller for levelling control of the load 60.

[0074] In various embodiments, the controller of the lifting system may be a PLC module. Under the control of the PLC module, each of the electric winches 114a/114b/114c/114d coupled with respective rotational encoders 113a/113b/113c/113d may independently adjust an operating length of each wire rope 112a/112b/112c/112d. The electric winches 114a/114b/114c/114d fixed or coupled to respective ones of the four corners of the frame 102 may independently release or pull up the respective wire ropes 112a/112b/112c/112d for adjusting the operating length and tension in each pulley wire rope system.

[0075] In various embodiments, the PLC module acts as the information and computation centre for the lifting system. The PLC module may be the control centre for performing auto-levelling of the load 60. The PLC module may receive sensor data from the sensors, such as

rotation signal(s) of the electric winch drums from the rotational encoders, tilt angle(s) of the load 60 from the inclinometer 140, tension data or tensile forces of the wire ropes from the load sensors 118. Thereafter, the PLC module may control the electric winches 114 based on auto-levelling algorithms and/or computational outputs from the auto-levelling algorithms, levelling the load 60 as shown in FIG. 7B. In addition, under the control of the PLC module, the moving mass 120 may be actuated or displaced to shift a centre of gravity of the frame 102 and the load 60 collectively. Concurrently with shifting the centre of gravity of the frame 102 and the load 60, the levelling adjustment is performed to cause a controllable lateral shift to the load 60 as shown in FIG. 7C.

[0076] As shown in FIGs. 7B and 7C, the provision of the pulley sets does not affect the operations of each of the pulley wire rope systems 110a/110b/110c/110d, thereby preserving the functions of auto-levelling (FIG. 7B), lateral shifting (FIG. 7C), yaw stabilizing, etc. For example, the load 60, such as a PPVC, may still be lowered or displaced downwards while maintaining the levelling with the configuration of four pulley wire rope systems 110a/110b/110c/110d.

[0077] As disclosed in previous sections, the lateral motion of the load 60 may be effected by shifting the overall centre of gravity of the load 60 and the frame 102. To facilitate the shift in centre of gravity, a sizable mass 120 may be moveably coupled to the frame 102. For example, the mass 120 may be coupled to two orthogonal linear tracks. The moving mass 120 may be driven to a desired position along the respective linear tracks using corresponding linear actuators along each direction of motion. In various embodiments, the greater the mass that is used on the tracks, the larger the corresponding lateral shift of the load 60 will be.

[0078] FIG. 8 is a top view of a lifting device 100 according to various embodiments. The lifting device 100 may include a mass 120 movable relative to the frame 102. The mass 120 may be movable along a first direction 123 and a second direction 125. The first direction 123

may be orthogonal to the second direction 125. In various embodiments, the lifting device 100 may include a first linear track 122 and a first linear actuator (not shown) coupled to the frame 102. The first linear track 122 may be arranged in line with the first direction 123, to permit movement of the mass 120 along the first direction 123. Under the actuation of the first linear actuator, the mass 120 may be moved to any position along the first linear track 122. Similarly, in various embodiments, the lifting device 100 may also include a second linear track 124 and a second linear actuator (not shown) coupled to the frame 102. The second linear track 124 may be arranged in line with the second direction 125, to permit movement of the mass 120 along the second direction 125. Under the actuation of the second linear actuator, the mass 120 may be moved to any position along the second linear track 124. Under the actuation of both the first linear actuator and the second linear actuator, the mass 120 may parallel to a main surface 104 of the frame 102. In various embodiments, the mass 120, the linear tracks 122/124 and linear actuators may be positioned on top of or underneath the frame 102. This may be done to maintain the lifting device 100 within a range of tilt angles, preferably substantially horizontal. It may be noted that excessive tilting to the frame 102 may reduce the effectiveness of the lifting system/device in altering or shifting a lateral position of the load 60 relative to the support 80.

[0079] FIGs. 9 to 11 show a flywheel gyroscope system 130 for yaw control according to various embodiments of the disclosure. The flywheel gyroscope system 130 may include a housing 132 coupled to the frame 102. The flywheel gyroscope system 130 may include a gimbal axle 134 moveable relative to the frame 102 and the housing 132. For example, the gimbal axle 134 may be controllably rotated 134a relative to the housing 132/frame 102, changing the orientation of the gimbal axle 134 relative to the frame 102. In various embodiments, a flywheel 132 may be provided rotatably coupled to the gimbal axle 134. The flywheel 132 may rotate 132a relative to the housing 132/frame 102 at a controllable rotational speed.

[0080] In various embodiments, the flywheel 132 may be sized according to the load 60 and/or the frame 102. The size of the flywheel 132 may correspond to the torque applied on the frame 102/load 60. For example, the flywheel 132 may be relatively large with a high mass for providing yaw control on a heavy load 60 and/or a heavy frame 102. In other examples, the flywheel 132 may be relatively small and light for providing yaw control on a lighter load 60 and/or a lighter frame 102. In various embodiments, the flywheel 132 may be rotatably mounted to a single gimbal axle. The flywheel 132 and gimbal may be mounted either on top of or underneath the frame 102.

[0081] In some embodiments, the axis of rotation 132a of the gimbal axle may be perpendicular to the yaw axis 95 (FIG. 2) of the load 60. The torque generated by the flywheel 132 and the gimbal axle 134 for yaw stabilization/control may correspond to the orientation of the rotating flywheel 132. For example, for a common rotational speed, the torque may be at a maximum when the flywheel 132 is vertical relative to the ground, and at a minimum when the flywheel 132 is horizontal, i.e. parallel relative to the ground. FIG. 10 shows a flywheel at an offset angle.

[0082] In various embodiments, the rotational speed of the flywheel 132 and the orientation of the gimbal axle 134 may be actively driven and independently controlled. The rotational speed or angular velocity of the flywheel 132 may be substantial in producing a sizable angular momentum to generate a torque on the frame 102 for yaw stabilizing/control. For example, the rotational speed of the flywheel 132 may be in the range of 2000 to 3000 revolutions per minute (RPM). In various embodiments, the rotational speed of the flywheel 132 may be controlled to maintain a target / predetermined rotational speed. The actuation/movement of the gimbal axle may transform the angular momentum of the flywheel 132 into the yaw-stabilizing torque. Therefore, by independently controlling each of the rotational speed of the flywheel 132 and the orientation of the gimbal axle 134, a torque applied on the frame 102 may be controlled.

[0083] In various embodiments, one or more gyroscopic sensors may be provided coupled to the frame and/or load to reliably provide respective yaw angles/yaw positions of the load and/or the frame. As the yaw angle of the load shifts, the flywheel gimbal axle may be rotated in response to generate a corrective torque. Referring to FIG. 11, by way of moving or rotating the gimbal axle, the angular momentum of the flywheel may be transformed into a torque about the yaw direction. With the gyroscopic sensor feedback from at least one of the gyroscopic sensors, the flywheel gyroscope system may provide a counter torque to the lifting device/load in the event the load begins to drift out of position due to an external disturbance, such as wind.

[0084] FIGs. 12A and 12B are schematic diagrams of the controller 400 and the respective communication channels/modes according to various embodiments of the lifting system. The controller 400 may include a main controller 410 coupled to the frame 102 for receiving control signals from the remote user controller 405 via wireless connection, for example via Wi-Fi connection. Further, the main controller 410 may be in signal communications with sub-controllers such as levelling controller 420, moving mass controller 430 and gyroscope controller 440. The sub-controllers 420/430/440 may be in signal communication with the main controller 410 via either wired connection or wireless connection, i.e. Ethernet or Wi-Fi.

[0085] In various embodiments, the lifting system may include a Wi-Fi router to provide a local wireless network. The user controller 405, the main controller 410, the levelling controller 420, the moving mass controller 430 and the gyroscope controller 440 may communicate and transfer data based on Transmission Control Protocol/Internet Protocol (TCP/IP) protocol in the local wireless network. The load sensor 118 and the gyroscopic sensor may output the respective sensor data through RS232 communication port to the respective levelling controller 420 and gyroscope controller 440. Further, the inclinometer 140 which is coupled to the load may send the sensor data through Wi-Fi directly to the levelling controller 420. The main

controller 410, the levelling controller 420 and the moving mass controller 430 may be connected to the same local network via ethernet to minimize communication time delay.

[0086] In various embodiments, the lifting system may include an industrial PC for system integration by facilitating effective communication between the main controller 410, the various sub-controllers 420/430/440 and the user(s). In some embodiments, TCP/IP model may be chosen as a widely used industry-standard model. However, other communication protocols may also be used. TCP/IP comprises a suite of communication protocols used to interconnect network devices on the internet or in a private computer network. TCP/IP uses the client-server model of communication in which a user or machine (a client) is provided a service by another computer (a server) in the network, such as receiving data. As shown in FIG. 7B, the industrial PC, i.e. main controller 410 may be programmed to act as an TCP server, while the levelling controller 420, the moving mass controller 430, the gyroscope controller 440, and the user(s)/operator(s) may act as the clients.

[0087] One of the features of the described multi-threaded TCP server is in the handling of clients based on their respective roles. Client roles may further be divided into two categories: sub-controllers and the user. In various embodiments, there may be three types of sub-controllers: the levelling controller 420, the moving mass controller 430, the gyroscope controller 440 as well as two types of users: admin user and normal user. FIG. 13 shows an example user interface (UI) of the user controller 405.

[0088] In various embodiments, the sub-controllers may include the following main tasks:

1. Send sensor data/ task updates to server.
2. Receive commands from server.
3. Inform the server of its current status.

[0089] In various embodiments, the role of admin user includes the following tasks:

1. Send commands.

2. Receive sensor data and progress updates from server.

[0090] Further, in contrast to the admin user, the role of normal user only includes the task of receiving sensor data and progress updates from server.

[0091] In various embodiments, the following safety precautions may be taken into consideration during the configuration of the main controller programme:

1. Only one admin user may be allowed at any moment to ensure safe operating procedure. Multiple normal users are allowed to provide real-time updates regardless of locations.

2. For commands requiring a certain period of time to execute, the intended controller system will be locked until the current execution is done. During the lock period, only the “stop” and status check related commands may be sent. Other commands will be ignored by the server and a warning will be issued to the admin user.

3. Emergency stop may be implemented to ensure that each of the sub-controller may be set to the safest operation mode when the command is sent/issued.

4. The status of all the clients may be closely monitored during the entire operation with any abnormal status detected and handled immediately.

[0092] In various embodiments, the process of auto-levelling may be performed/operated as a continuous process and/or a one-time process controlled by the operator. Referring to FIG. 14, the overall control process may include three stages or phases, namely: sensor input, decision making and action execution. Firstly, the control input may come from a) the 2-axis inclinometer coupled to the load such as a modular unit, which provides the roll and pitch angle and b) the four load sensors coupled to the respective wire ropes/cables, which measures the tension in the four wire ropes.

[0093] Based on the sensor inputs, adjustment(s) to the operating length of the wire rope(s) may be made if any of the wire ropes is slack. Levelling or angle adjustment to the load may

only be made when all wire ropes/cables are in tension. The electric winches may execute the adjustments/movements based on the controller output/command for cable adjustment and angle adjustment. Thereafter, a short time gap or pause may be provided to ensure all electric winches are not in action and the lifting system has come to a stationary state from a vibrational state caused by the stop. In various embodiments, the time gap/pause may be optimized based on the type of adjustment, i.e. cable adjustment or angle adjustment. Thereafter, the control loop may continue until both the roll threshold angle (α_r) and the pitch threshold angle (α_p) are achieved. The cable adjustment algorithm and load adjustment algorithm are illustrated in the following pseudo code:

Cable adjustment algorithm:

```

Input:  $load_i$ ,  $i = 1, 2, 3, 4$  //cable tension
Output:  $m_i$ ,  $i = 1, 2, 3, 4$  //winch movement
While True:
    For each  $load_i$  in loads:
        If  $load_i < Load_{min}$ :
            
$$m_i = k_{load} * (Load_{min} - load_i)$$

        End if
    End For
    If  $load_i \geq Load_{min}$  for all  $i$  in  $\{1, 2, 3, 4\}$ :
        Break
    End if
End While

```

Angle adjustment algorithm:

```

Input: roll, pitch
Output:  $m_i$ ,  $i = 1, 2, 3, 4$  //winch movement
While  $roll \geq \alpha_{roll}$  or  $pitch \geq \alpha_{pitch}$ :
    //PID Update:
    If  $\text{abs}(roll) > 2$ : //same for pitch
         $set\_point_{roll} = roll - \text{sign}(roll) * 2$  //set point is changing accordingly
        based on current angle reading
    Else:
         $set\_point_{roll} = 0$ 
    End If
    //PID Compute:
         $e_{roll} = roll - set\_point_{roll}$ 
         $I_{roll} = I_{roll} + (k_{I_{roll}} * e_{roll})$ 
         $PID_{roll} = k_{p_{roll}} * e_{roll} + I_{roll} + k_{d_{roll}} * (roll - last\_roll)$ 
         $m_{roll} = L_x * \sin(PID_{roll})$  //movement amount for winch
    //same for pitch
    For each  $m_i$ :
         $m_i = m_{roll} \pm m_{pitch}$ 
    End For
End While

```

Notes:

- 1) α_{roll} and α_{pitch} : This are the respective threshold angles for levelling algorithm to converge.
- 2) Cable loose: Every cable may have a minimum tension to avoid cable slack.
- 3) Precise winch movement: This is implemented by customized winch with rotational encoder and PLC control.

[0094] In various embodiments, the process of lateral shift of the load may be described as follows. The moving mass may be driven by the linear actuators. The control of the linear actuators may include the following considerations. Firstly, the linear actuators may be configured for smooth motion trajectories, i.e. to provide a gradual start and stop to the mass, minimizing or preventing vibration or jerking. Secondly, each of the linear actuators may be provided with positional control such that the moving mass may be moved/shifted from any position along the respective linear track to another position along the linear track. Thirdly, the control system may take in the desired position commands such that the desired position may be integrated into the controller/control system of the lifting system. In various embodiments, the sensor feedback provided for the control of the moving mass may be linear encoder readings from the respective linear actuators which may be directly translated into a linear position of the mass along the respective tracks.

[0095] In various embodiments, the process of yaw stabilization or yaw control of the frame/load may be described as follows. The yaw stabilization/control of the lifting system may rely on the rotational encoder feedback from the flywheel gyroscope system for maintaining a targeted rotational speed, i.e. RPM. Further, the rotational encoder feedback on the gimbal axle actuation may also be used to control both the position and velocity of the gimbal axle. The gimbal axle motion may be restricted such that the flywheel does not rotate past ± 90 degrees (assuming the vertical position is considered 0 degrees).

[0096] In various embodiments, to promote the efficiency of the lifting system on-site or in the field, the lifting system may be able to better conduct the operations which are typically performed manually by construction workers. The lifting system may perform designed procedures that correspond to each step of the actual conventional on-site practice with an improvement to efficiency. Table 1 illustrates the proposed operation procedures.

Table 1. Proposed operation procedures

Procedures	Actions				Location
	Crane	Winch	Moving Mass	Gyro	
System checking	Automatic system checking				Ground
Load unit & Initialization	Up	Off	Off	Off	
	Off	Initialization			
	Up	Off			
Levelling adjustment	Off	Level once	Off	Off	
System locked when the PPVC is transported from the ground to the final position					
Levelling adjustment	Off	Level once	Off	Off	Final position
Stabilization	Off	Keep levelling	Off	On	
Horizontal adjustment	Off	Keep levelling	On	On	
		Leveling once	Off		
Vertical adjustment	Off	Lower down	Off	On	
		Level once			
Unload Unit	Off	Lower down 10cm	Off	Off	
Level once: The auto-leveling process will end once PPVC is levelled.					
Keep levelling: The auto-leveling process will stay activated until user ends it.					

[0097] The operation procedure for horizontal adjustment utilizes the electric winches, the moving mass, and the gyroscope system collectively working together. It is notable that

although the movement of the moving mass may cause the orientation of the lifting system to change, the auto-levelling system and yaw stabilization system may be used to maintain the orientation of the lifting device/load allowing a stable orientation. For example, when the mass moves toward one side of the frame, both the frame and the load may be tilted to one side. In this process, the electric winches may automatically adjust the respective operating lengths of the wire ropes to minimize the tilt angles. Concurrently, the gyroscope system may also perform yaw control to maintain the yaw angle of the frame/load.

[0098] According to another aspect of the disclosure, FIG. 15 illustrates a method 700 of lifting a load. The method 700 may include, in 710, holding a load relative to a frame with a plurality of wire rope systems, the frame coupled to a support, wherein each of the plurality of wire rope systems comprises a wire rope with an independently adjustable operating length; in 720, receiving inputs from a plurality of sensors coupled to the frame, the plurality of sensors being configured to sense at least one parameter of the load; and in 730, based on the inputs from the plurality of sensors, independently adjusting the operating length of each of the wire rope. In various embodiments, the method 700 may further include levelling the load by independently adjusting the respective operating length of each of the wire rope.

[0099] In various embodiments, the method 700 may further include in 740, moving a mass relative to the frame to displace a centre of gravity of the frame to tilt the frame; and independently adjusting the operating length of each of the wire rope to laterally displace the load relative to the support. In various embodiments, the method 700 may further include in 750, providing a controllable torque on the frame by independently controlling: a rotational speed of a flywheel; and an orientation of a gimbal axle relative to the frame.

[00100] FIG. 16 illustrates an exemplary lifting system and device. To achieve more assembly benefits, e.g., fine adjustment control, less installation time and human resource, the intelligent lifting frame has sub-systems or sub-functions to stabilize and control the orientation

of lifted modular construction units in all six degrees of freedom. In the example, the mechanical sub-system may include a steel lifting frame, modular construction unit, and four pulley wire rope systems. The steel lifting frame, lifted by a four-leg chain under the crane hook, is fabricated to lift and hold the modular construction unit with pulleys and wire ropes. To achieve the proposed features, the frame also works as the platform to install the equipment including the winches, moving mass, gyroscope system and other related accessories. Further, the exemplary lifting system/lifting device includes three types of sensors deployed on the lifting system to monitor the attitude information and provide data input for different control systems. The sensors include the inclinometer, load sensors, and fibre optical gyroscopes. The inclinometer is mounted to the crane load while the load sensors are attached in series with each cable set. The fibre optic gyroscopes are mounted to the lifting frame and the crane load. Further, controllers and sub-controllers are provided to realize the core system functionalities controlled by the corresponding controllers/sub-controllers. For example, the four electric winches may be used for auto levelling, the two linear actuators may be used for lateral adjustment, and the flywheel with active gimbal axle control may be used for yaw stabilization and control.

1-tonne Prototype and Experiments

[00101] A scaled-down prototype of a lifting device/frame was constructed as shown in FIG. 17A, 17B, 18A and 18B. The prototype lifting device includes multiple on-board sub-systems and modules such as the automated electric winches, the flywheel gyroscope system, the moving mass, and an assortment of sensors. The overall lifting frame system weighed roughly 1-tonne with a mock-up load of 1-tonne. The frame was fabricated with a dimension of 2.9 meters long and 1.1 meters wide. See Figure 1 for more details. This prototype was used to validate the various features of the on-board subsystems.

Feature 1: Fast and accurate auto-levelling of the load (modular construction unit)

[00102] Simulation of the auto-levelling process is shown in FIGs. 19A to 19D, with FIGs. 19A and 19B showing the initial state of a tilted load; FIG. 19C showing the load in a levelled state; and FIG. 19D showing the levelling process.

[00103] To validate the concept and performance of the auto-levelling function, experiments were conducted. The experiments include three typical scenarios with varying tilt angles (large inclination, middle inclination, and small inclination), with the results from the experiments provided in Table 2. FIG. 20 shows the sensor data plot of roll angle and pitch angle as measured during the auto-levelling process. The results in Table 2 show that the auto levelling of load for the prototype lifting system can handle various inclination situations effectively and efficiently. It is also worth noting that the auto-levelling duration for a large pitch or roll angle are within 13 seconds.

Table 2. Auto-Levelling results of three typical scenarios

Test No.	Before Auto-Levelling (Degree)		After Auto-Levelling (Degree)		Auto-Levelling Duration (Second)
	Pitch	Roll	Pitch	Roll	
1	4.89	1.14	<0.1	<0.1	12.7
2	2.89	3.04	<0.1	<0.1	12.5
3	0.98	0.35	<0.1	<0.1	6.5

Feature 2: Fine lateral adjustment on the modular construction unit.

[00104] FIG. 21 shows the moving mass system of the exemplary lifting system. The moving mass system may include a motion range of 2.07 metres in the X-axis direction and 0.52 metres in the Y-axis direction. The moving mass system may shift the mass throughout the x-axis range and y-axis range.

[00105] FIG. 22 shows the results of lateral shifts in the load for the prototype lifting system, with an x-axis motion of 35mm overall (or +/- 17.5mm when moving from the centre) and a y-axis motion of 200mm overall (or +/- 100mm when moving from the centre).

Feature 3: Yaw stabilization on the load

[00106] FIG. 23 shows the orientation measurement of the load which is being forcefully disturbed in multiple instances, using the onboard gyroscopic sensor. It may be seen that the yaw stabilization as performed by the lifting system, uses the flywheel gyroscope system to generate counter torque(s) mitigating the external disturbances. In the experiments, the spinning flywheel was rotated about the gimbal axle, generating torque for stabilizing the lifting system and load along the yaw axis. Using the onboard sensors, the control system monitors the yaw angle or position as well as the angular velocity of the frame and load, and operates to reduce or remove any unwanted motion about the yaw axis. FIG. 24 shows an exemplary orientation response of active stabilization upon experiencing disturbance to the system.

Feature 4: Integrated control of the six degrees of freedom on the load

[00107] Experiments were performed on scenarios to demonstrate the capabilities of the proposed lifting system in controlling the motion(s) of the load while concurrently keeping the orientation(s) of the load stable. FIG. 25 shows the sensor data plot of load motions along the X-axis and Y-axis during motion adjustment. It may be seen that the motion along both directions are well controlled during motion without large/sudden fluctuations. FIG. 26 shows the sensor data plot of the roll angle, pitch angle, and yaw angle of the load during motion adjustment. Similarly, it may be seen that the roll, pitch and yaw angles were stabilized by the lifting system during motion, with the angular deviation reduced with time.

[00108] In various embodiments, the lifting system includes auto-levelling, lateral adjustment, and yaw stabilization which enables adjustment, stabilization and control of all the six degrees of freedom of the intended load, such as a lifted modular construction unit. This

contributes to high efficiency and accuracy in on-site assembly and construction as compared to conventional on-site practices. The lifting system was tested on a 1-tonne prototype with satisfactory results.

[00109] The lifting system and lifting device may be used to lift, move, and stabilize modular construction units, such as precast modular components inclusive of large PPVC modules, during hoisting operations. The lifting system and device may enable a fast and accurate auto-levelling process on the modular construction unit(s). With improvements in efficiency and reduction in manpower requirements, the lifting system/device significantly reduces the levelling operational time in comparison to conventional manual processes.

[00110] In addition, the lifting system and lifting device may perform fine lateral adjustment on the modular construction unit. Lateral adjustment is an important feature as the small tolerance in lateral movement required for on-site precast construction assembly is challenging and in some cases near impossible, via the present crane control. This feature provides fine lateral adjustment (with a resolution of 0.5 to 1 millimetres) or displacement to the modular unit when the load is close to the targeted position. In comparison, current typical tower cranes may only make relatively large-scale lateral adjustments (minimum of 0.5 metres adjustments) to the load constrained by the trolley precision and load sway.

[00111] Further, the lifting system and device may perform yaw stabilization or yaw control on the modular construction unit. Yaw stabilization may keep the lifted unit stabilized along the yaw axis (in the gravity direction) to withstand the wind and external disturbance, which is conventionally performed by workers pulling and dragging the load. Therefore, yaw stabilization may improve safety during the hoisting/lifting operation, reducing potential injuries to workers (such as falling, collision, etc) during the assembly process.

[00112] In addition, the lifting system and device may perform an integrated control of the six degrees of freedom on the lifted modular construction unit. This allows the lifting

system/device to independently control each degree of freedom of the load unit during the hoisting/lifting operation. For example, lateral adjustment may be achieved by moving a counter balance mass concurrently with complimenting auto-levelling and yaw stabilization for an efficient operation.

[00113] The present lifting system and lifting device may the following non-exhaustive benefits for an on-site construction application:

1. Crane load stabilization and control in all 6 degrees of freedom.
2. Crane load safety during load shifting/final set down.
3. Auto-levelling and yaw stabilization minimize the possibility of unwanted twisting or tilting.
4. With remote control of the crane load position and orientation, there is no need for tag lines or physical manipulation of the load before setting it down in its final position.
5. Crane load management manpower reduction:
 - 5.1 Reduces the number of workers required during the initial load levelling phase.
 - 5.2.Reduces the number of workers required during the final set-down phase.
6. Reduction in time taken for initial levelling of precast construction assembly.
7. With auto-levelling there is no need for manual trial-and-error approach of levelling the precast construction assembly
8. Minimizes/reduces the need for repeated set down tests, where some applications of precast construction assembly may often require multiple set down attempts, due to the trial and error nature of levelling and positional measurement.
9. On-board sensors with the loads position and orientation feedback minimize the number of set down attempts. In an ideal situation only one test placement would be needed with the final set down achieved on the second attempt.

[00114] All examples described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding, and are not intended to be limiting or exhaustive. Modifications may be made by one of ordinary skill in the art without departing from the scope of the invention as claimed.

CLAIMS

1. A lifting device comprising:
 - a frame couplable to a support;
 - a plurality of wire rope systems coupled to the frame, the plurality of wire rope systems being configured to hold a load relative to the frame, wherein each of the plurality of wire rope systems comprises a wire rope with an independently adjustable operating length; and
 - a plurality of sensors coupled to the frame, the plurality of sensors being configured to sense at least one parameter of the load.
2. The lifting device as recited in claim 1, wherein the respective operating length of each wire rope is independently adjustable to level the load relative to the support, responsive to inputs from the plurality of sensors.
3. The lifting device as recited in any one of the above claims, wherein each of the plurality of wire rope systems further comprises an electric winch coupled to the frame, each of the electric winch being configured to adjust the operating length of respective ones of the wire rope.
4. The lifting device as recited in any one of the above claims, wherein the plurality of sensors comprises a plurality of load sensors, each of the plurality of load sensors being coupled to respective ones of the wire rope and being configured to measure a tension in respective ones of the wire ropes.

5. The lifting device as recited in any one of claims 3 and 4, wherein at least one of the electric winches is coupled to each of a plurality of corners of the frame.
6. The lifting device as recited in any one of the above claims, further comprising an inclinometer removably coupleable to the load, the inclinometer being configured to determine an inclination of the load relative to the support.
7. The lifting device as recited in claim 6, wherein the inclination of the load comprises a first inclination angle along a first axis; and a second inclination angle along a second axis, wherein the first axis is orthogonal to the second axis.
8. The lifting device as recited in any one of the above claims, further comprising a mass moveably coupled to the frame, wherein responsive to moving the mass relative the frame, a center of gravity of the frame is displaced to tilt the frame.
9. The lifting device as recited in claim 8, wherein the mass is movable relative to the frame along a first direction and a second direction, wherein the first direction is orthogonal to the second direction.
10. The lifting device as recited in claim 9, further comprising a first linear actuator coupled to the frame, the first linear actuator being configured to move the mass along the first direction, and a second linear actuator coupled to the frame, the second linear actuator being configured to move the mass along the second direction.

11. The lifting device as recited in any one of the above claims, further comprising at least one flywheel gyroscope system coupled to the frame, each of the at least one flywheel gyroscope system being configured to provide a controllable torque to the frame.
12. The lifting device as recited in claim 11, wherein each of the at least one flywheel gyroscope system comprises:
 - a gimbal axle moveable relative to the frame; and
 - a flywheel rotatably coupled to the gimbal axle, wherein each of a rotational speed of the flywheel and an orientation of the gimbal axle is independently controllable to vary the torque on the frame.
13. The lifting device as recited in any one of the above claims, wherein the plurality of sensors comprises: a first gyroscopic sensor coupled to the frame, the first gyroscopic sensor being configured to determine an orientation of the frame; and a second gyroscopic sensor coupled to the load, the second gyroscopic sensor being configured to determine an orientation of the load.
14. The lifting device as recited in any one of the above claims, wherein the plurality of sensors comprises: at least one camera coupled to the frame, the at least one camera being orientated towards the load to provide an image of the load.
15. The lifting device as recited in any one of the above claims, wherein the load is a modular construction unit.
16. A lifting system comprising:

the lifting device as recited in any one of the above claims; and
a controller in signal communication with the lifting device, the controller being configured to control the lifting device to independently vary each of three translational degrees of freedom and each of three rotational degrees of freedom of the load.

17. The lifting system as recited in claim 16, wherein the controller is in a wireless signal communication with the lifting device.

18. The lifting system as recited in any one of claims 16 or 17, further comprising a user controller disposed remotely from and in wireless signal communication with the controller, the user controller being configured to transmit a control command from a user to the controller.

19. A method of lifting a load, the method comprising:

holding a load relative to a frame with a plurality of wire rope systems, the frame coupled to a support, wherein each of the plurality of wire rope systems comprises a wire rope with an independently adjustable operating length;

receiving inputs from a plurality of sensors coupled to the frame, the plurality of sensors being configured to sense at least one parameter of the load; and

based on the inputs from the plurality of sensors, independently adjusting the operating length of each of the wire rope.

20. The method as recited in claim 19, further comprising: levelling the load by independently adjusting the respective operating length of each of the wire rope.

21. The method as recited in any one of claims 19 and 20, further comprising moving a mass relative to the frame to displace a center of gravity of the frame to tilt the frame; and independently adjusting the operating length of each of the wire rope to laterally displace the load relative to the support.
22. The method as recited in any one of claims 19 to 21, further comprising: providing a controllable torque on the frame by independently controlling: a rotational speed of a flywheel; and an orientation of a gimbal axle relative to the frame.