

1 Control system for an articulated manipulator arm

2

3 The present invention relates to a control system
4 for an articulated manipulator arm, the manipulator
5 arm having at least three degrees of freedom,
6 preferably including at least two of a pivot axis, a
7 rotational axis and a translational axis. Every
8 joint or moveable axis on the manipulator arm is
9 referred to as a degree of freedom.

10

11 Manipulator arms are frequently used to perform
12 operations that a person is unable to carry out
13 unassisted or in environments that are too hazardous
14 and/or inhospitable for the presence of a human
15 operator, such as in deep sea or offshore
16 operations, areas exposed to high levels of
17 radiation or extra-terrestrial environments. Such
18 manipulator arms are usually controlled by a human
19 operator working in a safe location remote from the
20 manipulator arm, usually viewing the manipulator arm
21 and its surroundings via a video link.

22

1 Manipulator arms are used on subsea vehicles known
2 as ROVs (remotely operated vehicles). ROVs are used
3 for a variety of purposes, including salvage and
4 rescue operations, pipeline laying and maintenance
5 operations and other subsea activities at depths far
6 beyond that which can be reached by divers. Such
7 devices commonly operate at depths of 3000 metres or
8 more. The manipulator arm, and other functions of
9 an ROV are usually remotely controlled by an
10 operator on a surface vessel from which the ROV is
11 deployed.

12
13 A typical manipulator arm is shown in Figure 1. The
14 manipulator arm 1 comprises a base 2 mountable on a
15 structure, such as the body of an ROV, an upper arm
16 segment 3 pivotally attached to the base 2 for
17 rotation about a shoulder slew axis A and a shoulder
18 pitch axis B, a first forearm segment 4 pivotally
19 attached to the upper arm segment 3 for rotation
20 about an elbow pitch axis C, a second forearm
21 segment 5 rotatably mounted on the first forearm 4
22 segment for rotation about a forearm rotation or
23 roll axis D, a wrist segment 6 pivotally connected
24 to the second forearm segment 5 for rotation about a
25 wrist pitch axis E and a tool segment 7, having an
26 object manipulating tool comprising a pair of
27 opposed jaws 8 mounted thereon, the tool segment 7
28 being rotatably connected to the wrist segment 6 to
29 permit rotation of the tool about a tool rotational
30 axis F, the jaws of the object handling tool being
31 moveable between open and closed positions. Such
32 arrangement provides six degrees of freedom

1 providing a large operational envelope allowing a
2 wide range of manipulation operations to be carried
3 out:

4
5 Movement of the manipulator arm is usually driven by
6 hydraulic actuators (not shown), commonly a
7 combination of double acting hydraulic cylinders and
8 rotary actuators connectable to a source of
9 pressurised hydraulic fluid by means of electrically
10 operated hydraulic solenoid valves. Each hydraulic
11 actuator is usually associated with a pair of
12 valves, one for each direction of movement of the
13 actuator. The hydraulic solenoid valves are usually
14 mounted on a valve manifold. When the manipulator
15 arm is mounted on an ROV, the valve manifold and
16 source of pressurised hydraulic fluid is usually
17 mounted on the ROV adjacent the manifold.

18
19 There are two main known control systems for
20 controlling the operation of such manipulator arms.

21
22 A first control system is commonly known as rate
23 controlled or "bang-bang control". Simple hydraulic
24 solenoid valves are controlled by on-off switches
25 provided at an operator control station. Actuation
26 of a switch causes a selected valve to open,
27 supplying hydraulic fluid to an associated actuator
28 and causing the associated joint of the manipulator
29 arm to move in a selected direction at a fixed speed
30 (limited by the flow rate of the valve and subject
31 to the mechanical geometry) until the switch is
32 released, closing the valve and stopping movement of

1 the associated joint. The switches are usually
2 provided in pairs, associated with a simple joystick
3 or toggle, each pair of switches controlling a pair
4 of valves associated with a single actuator such
5 that movement of the joystick or toggle in one
6 direction causes movement of the associated joint in
7 a first direction and movement of the joystick or
8 toggle in the opposite direction causes movement of
9 the valve in a second direction, opposite to said
10 first direction.

11
12 Control systems of the bang-bang type provide slow
13 and crude control of the manipulator arm and are
14 unsuitable where accurate and precise control of the
15 manipulator arm is required. However, such systems
16 are relatively cheap, reliable and are easy to
17 maintain, requiring no wiring or electrical
18 components within the manipulator arm, thus reducing
19 the complexity of the arm thereby minimising the
20 sources of failure within the arm and facilitating
21 maintenance of the arm.

22
23 An improvement on the simple bang-bang control
24 system comprises the use of variable rate
25 (proportional) valves in place of fixed rate
26 hydraulic valves whereby the rate of flow of
27 hydraulic fluid to the actuators of the manipulator
28 arm, and thus the speed of movement of the arm, can
29 be controlled. In known variable rate systems the
30 variable rate valves are actuated by means of multi-
31 position switches or potentiometers connected to joy-
32 sticks whereby the speed of movement of a joint of

1 the manipulator arm is proportional to the magnitude
2 of movement of the joystick away from its home or
3 rest position. Such systems are more accurate than
4 the simple bang-bang system, but are still difficult
5 and time consuming to use, requiring a separate
6 control input for each joint of the manipulator arm.

7
8 A more accurate and intuitive system for controlling
9 a manipulator arm is the use of position feedback
10 control. This enables a master arm to be used to
11 control the manipulator arm (often referred to as
12 the slave arm). The master arm is effectively a
13 model or replica of the manipulator arm, albeit
14 usually on a smaller scale, the master arm having a
15 number of articulated segments interconnected by
16 joints, each joint of the master arm corresponding
17 to a joint of the manipulator arm to be controlled.

18
19 Each joint of the master arm has a position sensor,
20 in the form of a potentiometer, connected thereto
21 whereby the position of each segment of the master
22 arm with respect to the adjacent segments can be
23 determined by a controller. Similarly, each joint
24 of the manipulator arm is provided with a position
25 sensor to determine the position of each segment of
26 the manipulator with respect to the adjacent
27 segments.

28
29 When each master arm joint is moved, a computerised
30 control system senses the movement and controls the
31 operation of the proportional hydraulic solenoid
32 valves to move the corresponding joints of the

1 manipulator or slave arm by a corresponding or
2 proportional amount, using the output of the
3 position sensors of the manipulator arm to determine
4 when sufficient movement has taken place.
5 Electronic scaling can be used to vary the amount
6 the manipulator arm moves for a given movement of
7 the master arm.

8
9 Feedback control systems provide faster and more
10 accurate control of the slave manipulator arm and
11 provide a more intuitive control interface for the
12 operator. However, the need for position sensors in
13 each joint of the manipulator arm leads to a
14 requirement for wiring and other electrical devices
15 within the manipulator arm. In sub-sea
16 applications, such electrical devices need to be
17 protected from the environment in which the arm
18 operates by complex seals and compensation systems
19 (the filling of any voids or spaces within the arm
20 with incompressible fluids). This greatly increases
21 the cost of the manipulator arm, creates numerous
22 sources of unreliability (extensive wiring needs to
23 pass through each joint and continual flexing of the
24 joints leads to breakage of such wiring) and
25 increases the complexity and cost of maintenance
26 procedures. The feedback control system typically
27 requires the use of hydraulic servo valves, which
28 are more expensive and less tolerant to
29 contamination than the simple on-off valves used in
30 bang-bang systems.

31

1 An object of the present invention is to provide the
2 reliability and simplicity of the bang-bang control
3 system with the accuracy and intuitive control
4 interface of the feedback control system.

5
6 According to the present invention there is provided
7 a control system for an articulated manipulator arm,
8 the manipulator arm having at least three degrees of
9 freedom, said control system comprising a master
10 controller moveable to replicate the at least three
11 degrees of freedom of the manipulator arm; means for
12 determining the rate of movement of the master
13 controller in each direction replicating a degree of
14 freedom of the manipulator arm; and control means
15 for controlling actuation of the manipulator arm
16 whereby the rate of movement of the manipulator arm
17 in each of said at least three degrees of freedom is
18 proportional to the rate of movement of the master
19 controller in each direction replicating a degree of
20 freedom of the manipulator arm.

21
22 Preferably said at least three degrees of freedom of
23 the manipulator arm include at least two of a pivot
24 axis, a rotational axis and a translational axis.

25
26 In a preferred embodiment, the master controller
27 comprises an articulated master arm having a
28 plurality of arm segments interconnected by joints,
29 each joint of the master arm corresponding to a
30 joint the manipulator arm, the master arm having at
31 least three degrees of freedom corresponding to said
32 at least three degrees of freedom of the manipulator

1 arm such that movement of the master arm can
2 replicate movement of the manipulator arm. The
3 means for determining the rate of movement of the
4 master controller in each direction replicating a
5 degree of freedom of the manipulator arm may
6 comprise, for each joint of the master arm
7 corresponding to a joint of the manipulator arm,
8 means for sensing the relative position of the
9 segments of the master arm on either side of a the
10 joint and computing means for calculating the rate
11 of movement of said segments of the master arm with
12 respect to one another to determine the rate of
13 movement of the master arm about the joint of the
14 master arm replicating a joint of the manipulator.

15

16 Preferably the calculating means comprises a
17 differentiator for differentiating the position data
18 from the position sensing means to determine the
19 rate of movement of the segments of the master arm
20 about each joint of the master arm corresponding to
21 a joint of the manipulator arm.

22

23 Preferably the control system further comprises a
24 plurality of hydraulic actuators mounted on the
25 manipulator to move the manipulator in each of its
26 at least three degrees of freedom, each hydraulic
27 actuator being connectable to a source of
28 pressurised hydraulic fluid via a variable rate
29 valve, the control means controlling the opening and
30 closing of the variable rate valves to control the
31 rate of movement of the manipulator arm in

1 proportion to the determined rate of movement of the
2 master controller.

3

4 The master controller may include means for
5 selectively deactivating the control means to permit
6 movement of the master controller without causing
7 corresponding movement of the manipulator arm.

8

9 Preferably the manipulator arm has at least four
10 degrees of freedom. In a preferred embodiment the
11 manipulator arm has at least six degrees of freedom
12 comprising a shoulder yaw, a shoulder pitch, an
13 elbow pitch, a forearm rotation, a wrist pitch and a
14 wrist rotation, the master controller comprising an
15 articulated master arm having at least five degrees
16 of freedom corresponding to the shoulder yaw,
17 shoulder pitch, elbow pitch and forearm rotation of
18 the manipulator arm.

19

20 The control system preferably includes means for
21 controlling operation of an object manipulating tool
22 provided at a distal end of the manipulator arm.
23 Preferably the means for controlling the operation
24 of the object manipulating tool also controls the
25 wrist rotation of the manipulator arm. The means
26 for controlling the operation of the object
27 manipulating tool and wrist rotation of the
28 manipulator arm may comprise a single joystick
29 mounted on a distal end of the master arm to permit
30 one handed operation of the master arm.

31

1 Somewhat surprisingly, the control system according
2 to the present invention, based on a velocity master
3 slave relationship rather than a positional
4 relationship as with feedback control, has been
5 found to be practically indistinguishable in
6 operation from a feedback control system. The
7 control system according to the present invention is
8 actually more responsive than a feedback control
9 system as no closed position control loops are
10 present. This has the effect of removing any
11 stability issues that can occur in feedback systems
12 and is only limited in response by the finite delay
13 inherent in surface to subsea communications
14 systems, which is not usually noticeable and is
15 present in all subsea manipulator systems.

16
17 The system according to the present invention
18 provides fast, accurate and precise control of the
19 manipulator arm while also being as reliable and
20 easy to maintain as bang-bang systems.

21
22 An embodiment of the present invention will now be
23 described with reference to the accompanying
24 drawings in which:-

25
26 Figure 1 is a perspective view of a typical
27 manipulator arm, as discussed above;

28
29 Figure 2 is a perspective view of a typical master
30 arm for use with an embodiment of the control system
31 of the present invention;

32

1 Figure 3 is a schematic illustration of a control
2 system according to an embodiment of the present
3 invention.

4
5 As shown in Figure 2, the master arm 10 is
6 effectively a model or replica of the manipulator
7 arm 1, known as the slave arm. The master arm 10
8 has a number of articulated segments 20, 30, 40, 50,
9 60 interconnected by joints, each joint of the
10 master arm 10 corresponding to a joint of the
11 manipulator or slave arm 1 to be controlled. In the
12 embodiment described herein the master arm 10
13 comprises a base 20, an upper arm segment 30
14 pivotally attached to the base 20 for rotation about
15 a shoulder slew axis A' and a shoulder pitch axis
16 B', a first forearm segment 40 pivotally attached to
17 the upper arm segment 30 for rotation about an elbow
18 pitch axis C', a second forearm segment 50 rotatably
19 mounted on the first forearm 40 segment for rotation
20 about a forearm rotation or roll axis D' and a wrist
21 segment 60 pivotally connected to the second forearm
22 segment 5 for rotation about a wrist pitch axis E'.
23 Each of the pivot and rotational axes A', B', C', D', E'
24 of the master arm correspond to an axis of movement
25 (i.e. a joint) of the manipulator arm.

26
27 The wrist segment 60 of the master arm 10 is
28 provided with further control means for controlling
29 the rotation of the object manipulating tool of the
30 manipulator arm about the tool rotational axis F and
31 for controlling the operation of the jaws of the
32 object manipulating tool.

1
2 Obviously other designs of master arm are envisaged
3 depending on the type of manipulator arm which is to
4 be controlled. Other arms may have different
5 arrangements with more or less degrees of freedom
6 and may have one or more translational axis of
7 movement in addition to, or instead of rotary or
8 pivotal axes.

9
10 A position sensor, in the form of a potentiometer,
11 is provided on each joint of the master arm 1, the
12 output of the each position sensor being fed to a
13 computer 100 (see Figure 3) which provides a control
14 signal for the manipulator arm controller 200 which
15 in turn controls operation of the manipulator arm
16 actuator 300.

17
18 A position sensor other than a potentiometer may be
19 used at each joint of the master arm.

20
21 The master arm 10 provides a particularly intuitive
22 and easy to use control interface for the operator.
23 However, master arms have only been suitable in the
24 past for position feedback control devices. The
25 control system according to the present invention
26 permits the use of a master arm as shown in Figure 2
27 to control a manipulator arm of the type shown in
28 Figure 1, without requiring the manipulator arm to
29 be provided with any position determining means,
30 such as potentiometers or other position sensing
31 electronics (i.e. no position feedback from the
32 manipulator arm is required).

1

2 Figure 3 is a schematic illustration of a
3 manipulator arm control system according to an
4 embodiment of the present invention. The master arm
5 10 and computer 100 are provided at an operator
6 station 110. When the manipulator arm 1 is mounted
7 on an ROV 220, the operator station 110 would be
8 provided on a surface vessel from which the ROV is
9 deployed, the operator station 110 being connected
10 to the ROV 220 by a communications link.

11

12 Movement of the manipulator arm 1 is driven by a
13 plurality of double acting hydraulic actuators,
14 either linear or rotary as appropriate, provided on
15 the manipulator arm and connected to variable rate
16 hydraulic solenoid valves mounted on a valve
17 manifold 300. The valve manifold 300 is provided on
18 the ROV, along with a source of pressurised
19 hydraulic fluid (usually an electric pump connected
20 to a reservoir of hydraulic fluid). A manipulator or
21 slave arm controller 200 is provided adjacent the
22 valve manifold 300 for controlling the actuation of
23 each variable rate valve. With this arrangement,
24 there are no electronics or vulnerable wiring on the
25 manipulator arm itself, the actuation means of the
26 manipulator arm being similar to that of the known
27 variable rate systems described above, with the
28 inherent advantages of reliability, low cost and
29 ease of maintenance.

30

31 The computer 100 calculates the rate of change of
32 position of each joint of the master arm 10 by

1 differentiating the output signals received from the
2 position sensors of the master arm 10, thus
3 determining the rate or speed of movement of each
4 joint. The computer 100 sends a control signal to
5 the manipulator or slave arm controller 200,
6 provided on the ROV, based upon said calculated rate
7 of movement information. Based upon said control
8 signal the slave arm controller 200 controls the
9 operation of the variable rate valves to move each
10 joint of the manipulator or slave arm 1 at a rate or
11 speed proportional to the rate of movement of the
12 corresponding joint of the master arm 10.

13
14 The computer 100 includes selectable electronic
15 scaling means whereby the relationship between the
16 rate of movement of the master arm 10 and the
17 resulting rate of movement of the manipulator or
18 slave arm 1 can be varied by the operator between
19 that required for rapid and large movements of the
20 manipulator arm 1 and that required to permit small
21 and accurate movements of the manipulator arm 1 and
22 its object manipulating tool. The master arm 10 can
23 also be provided with control means to selectively
24 freeze the movement of individual joints or groups
25 of joints of the manipulator arm and/or to
26 selectively permit free movement of the master arm
27 10 without resulting movement of the manipulator arm
28 1 to enable the master arm to be re-indexed.

29
30 The wrist segment of the master arm 10 includes
31 control means for controlling rotation of the object
32 manipulating tool 8 about the tool rotational axis D

1 and for controlling operation of the jaws of
2 thereof. The rotation control may comprise a simple
3 direction switch controlling rotation of the tool in
4 either direction at a fixed rate or may control the
5 rate of rotation of the tool, either by the known
6 variable rate control method whereby the speed of
7 rotation is proportional to the displacement of a
8 control device, such as a joystick or thumb wheel,
9 from an index position, or by a proportional rate
10 control whereby the rate of rotation of the tool is
11 proportional to the rate of movement of a control
12 device, e.g. a thumbwheel or rotatable section. The
13 control of the jaws of the tool may be controlled by
14 a simple two way switch.

15

16 In one embodiment the tool rotation control and jaw
17 control may be integrated into a single joystick
18 whereby movement of the joystick in a first plane
19 (e.g. forwards and backwards) causes opening and
20 closing of the jaws of the tool and movement in a
21 plane normal to the first plane (e.g. side to side)
22 causes rotation of the tool about the wrist axis.

23

24 In an alternative embodiment (not shown) speed
25 sensors might be provided on each joint of the
26 master arm to directly measure the rate of movement
27 of each joint of the master arm, thus obviating the
28 need to differentiate position information and
29 simplifying the control algorithms of the computer
30 100.

31

1 In another embodiment, a master controller other
2 than a master arm might be used, such as one or more
3 joysticks. The master controller would be moveable
4 to replicate the movement of each joint (degree of
5 freedom) of the manipulator arm to be controlled,
6 the control system including means for determining
7 the rate of movement of the master controller in
8 each direction replicating joint of the manipulator
9 arm, either by directly measuring the rate of
10 movement of the master controller or by sensing the
11 position of the master controller and calculating
12 the rate of movement thereof from the positional
13 information. The computer 100 and manipulator arm
14 controller 200 would control actuation of the valves
15 of the valve manifold 300 to control movement of the
16 manipulator arm whereby the rate of movement of each
17 joint of the manipulator arm to be controlled is
18 proportional to the rate of movement of the master
19 controller in the corresponding direction.

20

21 Whilst the present invention has been described
22 applied to a manipulator arm for use on an ROV in a
23 subsea environment, the control system according to
24 the present invention may also be advantageously
25 applied to a control manipulator arm in a variety of
26 other applications, such as in the nuclear industry
27 to operate in areas exposed to high levels of
28 radiation and in extra-terrestrial applications or
29 any other application where manipulator arms may be
30 used.

31

1 In addition to hydraulic actuators, the control
2 system of the present invention may be utilised to
3 control manipulator arms having other actuation
4 means, such as electric drives (e.g. servomotors,
5 stepper motors) or pneumatic drives (i.e. air driven
6 actuators).

1 Claims

2

3 1. A control system for an articulated manipulator
4 arm, the manipulator arm having at least three
5 degrees of freedom, said control system comprising
6 a master controller moveable to replicate the at
7 least three degrees of freedom of the manipulator
8 arm; means for determining the rate of movement of
9 the master controller in each direction
10 replicating a degree of freedom of the manipulator
11 arm; and control means for controlling actuation
12 of the manipulator arm whereby the rate of
13 movement of the manipulator arm in each of said at
14 least three degrees of freedom is proportional to
15 the rate of movement of the master controller in
16 each direction replicating a degree of freedom of
17 the manipulator arm.

18

19 2. A control system as claimed in claim 1, wherein
20 said at least three degrees of freedom include at
21 least two of a pivot axis, a rotational axis and a
22 translational axis.

23

24 3. A control system as claimed in claim 1 or claim
25 2, wherein the master controller comprises an
26 articulated master arm having a plurality of arm
27 segments interconnected by joints, each joint of
28 the master arm corresponding to a joint of the
29 manipulator arm, the master arm having at least
30 three degrees of freedom corresponding to said at
31 least three degrees of freedom of the manipulator

1 arm such that movement of the master arm can
2 replicate movement of the manipulator arm.

3
4 4. A control system as claimed in claim 3 wherein
5 said means for determining the rate of movement of
6 the master controller in each direction
7 replicating a degree of freedom of the manipulator
8 arm comprises, for each joint of the master arm
9 corresponding to a joint of the manipulator arm,
10 means for sensing the relative position of the
11 segment of the master arm on either side of the
12 joint and computing means for calculating the rate
13 of movement of said segments about said joint to
14 determine the rate of movement of the master arm
15 about the joint of the master arm replicating a
16 joint of the manipulator.

17
18 5. A control system as claimed in claim 4, wherein
19 the calculating means comprises a differentiator
20 for differentiating the position data from the
21 position sensing means to determine the rate of
22 movement of the segments of the master arm about
23 each joint of the master arm corresponding to a
24 joint of the manipulator arm.

25
26 6. A control system as claimed in claims 1, 2 or 3
27 wherein the means for determining the rate of
28 movement of the master controller comprises speed
29 sensing means capable of sensing the speed of
30 movement of the master controller in each
31 direction replicating a degree of freedom of the
32 manipulator arm.

1

2 7. A control system as claimed in any preceding
3 claim further comprising a plurality of hydraulic
4 actuators mounted on the manipulator to move the
5 manipulator in each of its at least three degrees
6 of freedom, each hydraulic actuator being
7 connectable to a source of pressurised hydraulic
8 fluid via a variable rate valve, the control means
9 controlling the opening and closing of the
10 variable rate valves to control the rate of
11 movement of the manipulator arm in proportion to
12 the determined rate of movement of the master
13 controller.

14

15 8. A control system as claimed in any preceding
16 claim wherein the master controller includes means
17 for selectively deactivating the control means to
18 permit movement of the master controller without
19 causing corresponding movement of the manipulator
20 arm.

21

22 9. A control system as claimed in any preceding
23 claim wherein the manipulator arm has at least
24 four degrees of freedom.

25

26 10. A control system as claimed in any preceding
27 claim wherein the manipulator arm has at least six
28 degrees of freedom comprising a shoulder yaw, a
29 shoulder pitch, an elbow pitch, a forearm
30 rotation, a wrist pitch and a wrist rotation, the
31 master controller comprising an articulated master
32 arm having at least five degrees of freedom

1 corresponding to the shoulder yaw, shoulder pitch,
2 elbow pitch and forearm rotation of the
3 manipulator arm.

4

5 11. A control system as claimed in any preceding
6 claim the control system including means for
7 controlling operation of an object manipulating
8 tool provided at a distal end of the manipulator
9 arm.

10

11 12. A control system as claimed in claim 11 when
12 dependent on claim 10, wherein the means for
13 controlling the operation of the object
14 manipulating tool also controls the wrist rotation
15 of the manipulator arm.

16

17 13. A control system as claimed in claim 12,
18 wherein the means for controlling the operation of
19 the object manipulating tool and wrist rotation of
20 the manipulator arm comprises a single joystick
21 mounted on a distal end of the master arm to
22 permit one handed operation of the master arm.

23

24