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Remote handling devices for radioactive materials —

Part 3: Electrical master-slave manipulators

*Dispositifs de manipulation à distance pour matériaux radioactifs —
Partie 3: Télémanipulateurs maître-esclave électriques*

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Foreword

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ISO 17874-3 was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

ISO 17874 consists of the following parts, under the general title *Remote handling devices for radioactive materials*:

- *Part 1: General requirements*
- *Part 2: Mechanical master-slave manipulators*
- *Part 3: Electrical master-slave manipulators*
- *Part 4: Power manipulators*
- *Part 5: Remote handling tongs*

Introduction

This part of ISO 17874 deals with electrical master-slave manipulators used for nuclear applications. These are multipurpose remote handling devices used to replace hands and arms in areas hazardous or inaccessible to personnel (typically behind shielding walls).

Electrical master-slave manipulators were originally developed for large hot cells designed for research and development of fuel elements for nuclear reactors. They are now commonly used for other nuclear purposes, such as reprocessing, accelerator plants and decommissioning of redundant nuclear facilities. A different field of application features manipulators mounted on vehicles for use, e.g. in situations involving recovery radioactive sources or contaminated objects from incidents and accidents.

Electrical master-slave manipulators can be modified or specially designed for non-nuclear applications. This part of ISO 17874 does not address the special requirements of such fields, although designers might be able to take advantage of the standardized features and components from the nuclear sector to achieve efficient and cost-effective designs for other applications, where appropriate.

This part of ISO 17874 is intended to provide assistance to designers of nuclear process and research plants and their equipment, as well as to manufacturers and users of electrical master-slave manipulators and associated regulatory authorities.

Remote handling devices for radioactive materials —

Part 3: Electrical master-slave manipulators

1 Scope

This part of ISO 17874 specifies the main features of electrical master-slave manipulators intended to be used for nuclear applications. It outlines basic principles which relate to the design features of electrical master-slave manipulators for applications both inside and outside nuclear plant buildings.

This part of ISO 17874 does not address prototypes, experimental devices and obsolete types, involving variations in design which omit one or more essential features of electrical master-slave manipulators (e.g. force reflection). Examples of such devices and special features are given in Annex A.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 17874-1:2010, *Remote handling devices for radioactive materials — Part 1: General requirements*

ISO 17874-2:2004, *Remote handling devices for radioactive materials — Part 2: Mechanical master-slave manipulators*

ISO 17874-4:2006, *Remote handling devices for radioactive materials — Part 4: Power manipulators*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1

electrical master-slave manipulator

system reproducing the movements of hand and arm of the operator by means of isokinematic master and slave arms with bilateral electrical position control (force reflection)

NOTE 1 The word “bilateral” refers to the property of the system to be indifferently moved by acting on the master arm or on the slave arm.

NOTE 2 The slave arm is generally mounted on a transporter (mobile).

3.2

arm

component reproducing the functions of a human arm, respecting in most cases the same distribution and corresponding articulations

NOTE The corresponding articulations include shoulder pivot, upper arm, elbow pivot, forearm and wrist pivot.

3.3

axis

direction of a Cartesian coordinate system defined from the operator's standpoint, considered as the origin of the system

NOTE The following axes are considered:

- axis X: from the right to the left along the shielding wall;
- axis Y: forward into the shielded cell;
- axis Z: towards the ceiling of the shielded cell.

3.4

balancing

characteristic allowing the manipulator to be maintained with negligible forces applied by the operator in stable positions throughout the whole operating volume by electrical or mechanical means (e.g. counterweights)

3.5

gaiter

specially profiled flexible sleeve designed to protect the slave arm from contamination

NOTE This component is also called a booting (US).

3.6

handle

component fixed at the end of the master arm and gripped by the operator, facilitating the control of the movement of the manipulator

3.7

indexing motion

X, Y and Z motion

adjustable electrical displacement between the slave arm position and the corresponding master arm position, to enlarge the operating volume and minimize operator strain

3.8

jaws

components fixed on the end of the tongs which facilitate the handling of the objects

NOTE The jaws can be disconnectable.

3.9

master arm

arm located outside a hot cell and equipped with an operator handle on which the operator acts

3.10

range of motion

range over which a motion can be executed by a sub-assembly

3.11

orientation motion

rotation motion around certain axes of the tongs

NOTE Depending on the axis considered, three rotational motions are distinguished:

- tilt (α),
- twist (β), and
- swivel or azimuth motion (γ).

3.12**operating volume****operating range**

space in which the operation of the tongs is possible, considering all the positions in which the different components of the slave arm of a manipulator can be moved

3.13**positioning motion**

motion affecting a displacement of the tongs (or end effector)

NOTE Depending on the axis considered, three different motions are distinguished: X, Y and Z.

3.14**PLZT****lead lanthanum zirconium titanate**

electro-optical crystal medium used to switch rapidly between orthogonal linear polarizations in three-dimensional visualization systems

3.15**slave arm**

arm located inside a hot cell, for example, and equipped with tongs to grip objects or tools, or mounted on a transporter

3.16**tongs**

gripping device fixed at the end of the slave arm and consisting of a hand assembly including the jaws

3.17**transmission element**

mechanical element which transmits motive force or torques from the drive unit(s) to the arm sub-assemblies to be moved

3.18**transporter**

kinematic system for moving and positioning the slave arm or slave unit within the operating volume

3.19**isokinematic**

property of a manipulator where, from base to free end, the master arm and slave arm present the same type of motion (rotation or translation) in the same order and with the same relative orientations

4 Field of application

Electrical master-slave manipulators are typically used inside buildings, in large hot cells for research, nuclear fuel reprocessing plants, waste treatment plants, accelerators, fusion research machines and large enclosures for other purposes where high radiation levels or radioactive contamination are encountered.

The tasks to be performed include normal operations, maintenance, repair, exchange of process components, interventions, recovery and decommissioning.

Electrical master-slave manipulators are suitable for complicated high-dexterity tasks similar to those for which a mechanical master-slave manipulator would be used, but with the possibility to reduce the force perceived by the operator. Their operating volume can be greatly increased by means of a transporter. Electrical master-slave manipulators combine most of the advantages of mechanical master-slave manipulators (particularly dexterity, see ISO 17874-2) and power manipulators (notably mobility, see ISO 17874-4). Accordingly, they can be used for work in areas that cannot be reached by fixed mechanical master-slave manipulators. Heavy objects can be handled more easily than with mechanical master-slave manipulators by using servo assistance, and in a shorter time than with power manipulators by employing isokinematic master-slave control.

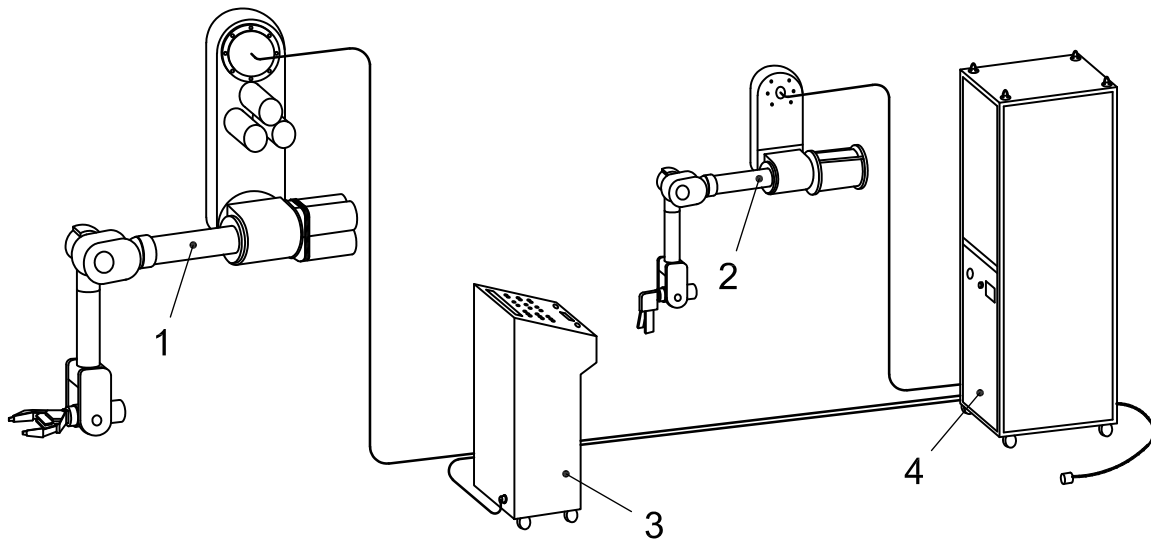
One pair of electrical master-slave manipulators can advantageously be installed instead of several pairs of mechanical master-slave manipulators in a hot cell with shielding windows, if it is not necessary to operate on many of the working stations (windows) at the same time.

5 General features

An electrical master-slave manipulator generally consists of four typical sub-assemblies (see Figure 1):

- one slave arm,
- one master arm,
- an operating desk or console, and
- a control cabinet.

The slave arm and the master arm are usually built with different load capacities. In special applications, two control cabinets are provided, one each for the slave arm and the master arm, e.g. if the control for the slave arm needs to be located remotely.



Key

- 1 slave arm
- 2 master arm
- 3 operating desk (or console)
- 4 control cabinet

Figure 1 — Electrical master-slave manipulator — Sub-assemblies

In the standard mode of working, a force or a displacement is applied on the master arm, with a corresponding effect on the slave arm. However, the master and slave arms shall both be back-drivable, i.e. if a force or a displacement is applied to the slave arm, the master arm shall follow. Consequently, the actuator transmissions shall be mechanically back-drivable and the electric motor drive system shall provide “force reflection” of load on the slave arm to the operator, via the handle of the master arm. It shall be possible to introduce a ratio in the force reflection so that the slave arm executes higher forces than are felt by the operator.

The slave arm shall be electrically coupled to the master arm in such a manner that the differences of velocities and displacements between the corresponding components of the master arm and the slave arm remain very small. The motions the operator makes with the handle of the master arm and the forces and torques that he supplies to the handle shall be transmitted to the slave arm with a delay imperceptible to the operator for the task concerned.

The slave arm is generally installed on a transporter in order to attain a large operating volume, where a wide range of positions is to be achieved. The transporters are generally designed to run on rails, typically located overhead. The slave arm can also be installed on a remotely controlled vehicle running on the ground for use inside or outside buildings. Electrical master-slave manipulators can be installed in pairs to carry out complicated tasks.

6 Requirements

6.1 General aspects

Electrical master-slave manipulators shall meet a number of general technical requirements in addition to the specific features above.

Each motion of the master arm of an electrical master-slave manipulator shall be connected by a bilateral position control circuit (see 6.11) to the equivalent motion of the slave arm.

The friction force the operator has to overcome when he moves the manipulator in the no-load condition shall be kept as low as possible in order not to reduce the dexterity or to tire the operator unnecessarily (see 6.7).

The deflections due to loading of the slave arm sub-assemblies shall be kept small compared to the changes made in the orientation of the corresponding sub-assemblies of the master arm, in order not to reduce the dexterity (see 6.8). This means that a compromise shall be found between low friction and minimized backlash and elastic deflection under load.

The drive unit inertia shall be kept sufficiently low to limit operator fatigue when moving the mass of the arms quickly. The resistance to motion of the master arm felt by the operator when moving the arm at normal speed should not be perceptibly larger than the frictional and inertial forces of the master arm alone.

It shall be possible for the slave arm to follow the motions of the master arm at speeds up to 1 m/s for translations and 1 r/s for orientation motions (see 6.9), each with imperceptible lag.

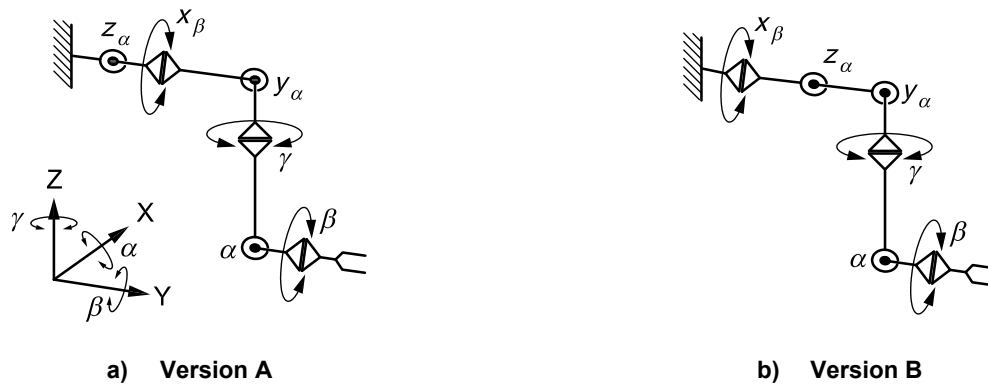
The dead weight of the sub-assemblies of the slave arm and the master arm shall be compensated. This is necessary at least for the following motions:

- inclination of upper arm,
- rotation of upper arm, and
- inclination of forearm.

Electrical master-slave manipulators also need to satisfy plant safety requirements regarding the operating environment (e.g. the presence of contamination, ionizing radiation, corrosive atmosphere, excessive humidity or temperature).

6.2 Motions

Electrical master-slave manipulators shall have seven motions (three positioning motions, three orientation motions and one gripping motion) accommodated by the master arm and the slave arm and corresponding to the requirements of ISO 17874-1:2010, Clause 4, for multipurpose remote handling devices. The kinematics of the electrical master-slave manipulators shall correspond to ISO 17874-1:2010, 6.2 (see Figure 2).



NOTE The difference between versions A and version B is the exchange of the motions Z_α and X_β . With version B, the operating volume is increased by the rotation of the shoulder pivot.

Figure 2 — Electrical master-slave manipulator — Slave arm (kinematics diagram)

6.3 Load capacity

Depending on the model of the electrical master-slave manipulator, the load capacity of the slave arm ranges from under 10 kg up to 100 kg. Three classes concerning the maximum load, defined as that handled by the tongs, shall be distinguished:

- light-capacity electrical master-slave manipulators: up to 10 kg;
- medium-capacity electrical master-slave manipulators: from 10 kg to 45 kg;
- heavy-capacity electrical master-slave manipulators: from 45 kg to 100 kg.

The slave arm shall be able to handle the maximum load in any position and orientation to which the operator can move the master arm.

It should be noted that when accelerating the load, the operator and the master-slave equipment have to accommodate the inertial forces (even if the dead weight has been compensated).

The slave arm shall be able to hold stationary (at any position and orientation) an object with a weight equal to the maximum load, for at least 30 min, without using any brakes.

6.4 Length of the slave arms

The length between the wrist pivot and the shoulder pivot of a slave arm lies typically within the range of 1,0 m to 1,9 m.

The usual length for each of the different classes is as follows:

- light-capacity electrical master-slave manipulators: from 1 000 mm to 1 200 mm;
- medium-capacity electrical master-slave manipulators: from 1 050 mm to 1 900 mm;
- heavy-capacity electrical master-slave manipulators: from 1 400 mm to 1 800 mm.

The hand assembly introduces an additional length, which ranges from 150 mm for light manipulators to 350 mm for heavy manipulators.

With regard to the dexterity, the hand assembly should be as short as possible.

6.5 Forces, torques and lengths

Table 1 specifies the minimum lengths, forces and torques characterizing a seven-motion electrical master-slave manipulator.

Table 1 — Forces, torques and lengths

Parameter	Manipulator class			
	Light capacity	Medium capacity		Heavy capacity
		(a)	(b)	
Maximum load, kg	10	24	45	100
Upper arm length, mm	460	700	700	800
Forearm length, mm	560	900	900	800
Force of inclination of upper arm, daN	10	24	45	100
Force of rotation of upper arm, daN	10	24	45	100
Force of inclination of forearm, daN	10	24	45	100
Force of rotation of forearm, daN	1,4	4,5	8	24
Force of inclination of tongs, daN	1,5	4	7,5	24
Force of rotation of tongs, daN	1,4	4	7,5	20
Gripping force, daN	14,5	30	60	130

NOTE If the arms are lengthened or shortened compared to the lengths quoted in this table (e.g. for special applications), the load capacity and the forces of inclination and rotation of the upper arm and the forces of inclination of the forearm will be reduced or increased respectively.

6.6 Design features

6.6.1 Main features

The slave arm and master arm of an electrical master-slave manipulator shall be divided into four sub-assemblies:

- hand assembly (slave arm) or handle (master arm),
- forearm,
- upper arm, and
- drive system.

Depending on the model, the drive system consists either of two distinct drive blocks (see Figure 3) or of one drive housing containing all the drive units (see Figure 4). The upper arm is generally orientated horizontally and the forearm vertically, when in the basic position.

The pivots of an arm are the wrist pivot, elbow pivot and shoulder pivot (see Figure 4). Each motion of the slave arm and the master arm shall be equipped with one drive unit. Such a drive unit shall consist of one or several motors, a gearing, which provides a basic reduction, a position transducer and a brake. Optionally, a tachometer may be used in addition.

The drive units shall be interchangeable to minimize spares holding as much as possible. These drive units shall be arranged behind the shoulder pivot as seen from the tongs or handle, respectively, in order to minimize the weight of the arm sub-assemblies. This helps the realization of a slender arm, which is advantageous with regard to working in restricted spaces.

Consequently, for the orientation motions and the gripping motion, transmission elements shall run from the drive units to the associated arm sub-assemblies. These are typically steel cables and/or steel tapes.

The slave arm shall be equipped with tongs with parallel moving jaws (standard tongs), by means of which objects can be handled and forces and torques can be exerted on objects. The dimensions for standard tongs are given in 6.10. This allows the adaptation of the gripping location of objects and tools to suit the dimensions of the jaws.

For electrically driven tools, a socket for electrical current shall be provided. Optionally, a multiple coupling for electricity, welding, hydraulic and pneumatic services can be incorporated, which should be mounted on an appropriate position on the slave arm or slave unit. Connection devices shall be designed for successful remote operation in a hostile environment (e.g. with grit and corrosive chemicals present).

The parallel jaws of the tongs, or half of the tongs, or the complete tongs assembly, shall be remotely exchangeable by means of an in-cell fixture or another slave arm. If the parallel jaws are exchangeable, the complete tongs can optionally be exchanged remotely.

The slave arm can be arranged to be exchangeable remotely.

The positioning and orientation motions of the slave arm and of the master arm shall be lockable by brakes. Generally, if no force is exerted at the handle, the tongs shall be opened automatically by an appropriate means. However, the gripping motion shall be lockable by a switch at the handle in order to relieve the operator from having to sustain the gripping force.

Overload protection shall be provided for the mechanical sub-assemblies of the kinematic systems (e.g. slipping clutch, motor current limitation).

Electrical master-slave manipulators shall be easy to decontaminate and maintain; in the case of maintenance, this applies in particular to bearings, couplings, gears and motors. Electrical master-slave manipulator sub-assemblies and components shall be simple to mount and dismount. Drive units and electric cables shall be easy to replace. Sub-assemblies of the same nominally identical model shall be interchangeable. Similarly, it shall be possible to interchange sub-assembly parts within one model. If the equipment available in the hot cells does not offer any alternative recovery option, then suitable devices shall be provided for the adjustment or shifting of the motions concerned, in the event of failure of any of the drives.

To facilitate decontamination, intermittent welds and spot welds shall be avoided in the sub-assemblies of the electrical master-slave manipulators. All welds shall avoid poor alignment of the edges and be free of cracks and other defects, in order to minimize decontamination problems.

Welds which are exposed to contamination in service shall be such that the quality of the weld surface corresponds to the quality of the adjacent surfaces.

6.6.2 Design concepts

6.6.2.1 General features

The transmission elements of the motions comprising inclination of upper arm and inclination of forearm shall be designed in such a manner that they have synergistic features and support each other. Thus, the drive units for both motions can be of the same type.

The drive units for rotation of tongs and inclination of hand shall be coupled together by a differential gear in the hand assembly. Accordingly, if the rotations of these drive units have different directions, the tongs are rotated; and if they have the same direction, the tongs are inclined.

Three different design concepts are standardized, each one corresponding to a different electrical master-slave manipulator class.

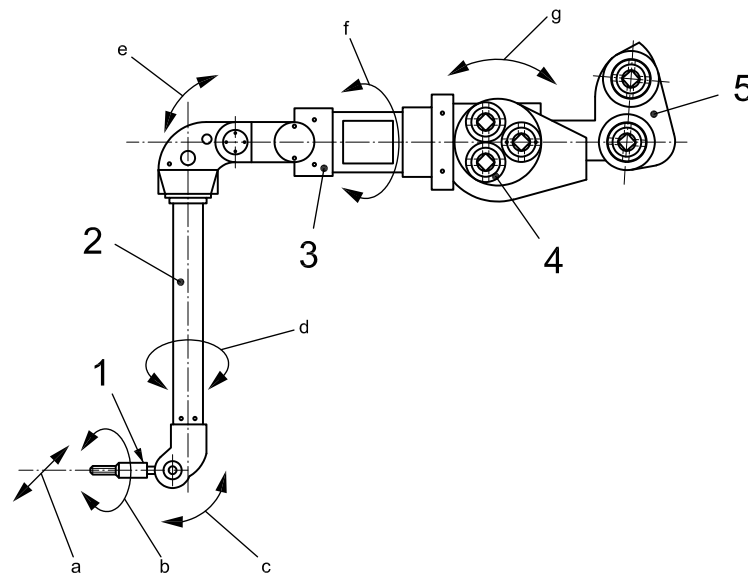
6.6.2.2 Light-capacity electrical master-slave manipulators

For these models, one type of motor is used for all motions of the slave arm and master arm.

The drive units for the positioning motions are arranged to form a block at the shoulder pivot. The positioning motions are driven by gear wheels. The drive units for the orientation motions and gripping are typically installed on a moveable boom behind the shoulder pivot and are also used for counterbalancing in order to reduce the weight of the arm (see Figure 3). The orientation and gripping motions are driven by steel cables or steel tapes, as transmission elements inside the arm components.

The drive units consist of one type of d.c. motor.

NOTE In the example in Figure 3, the ranges of motions partly exceed the values quoted in Table 2.



Key

- 1 tongs
- 2 forearm
- 3 upper arm
- 4 drive unit assembly of motions 5 to 7
- 5 drive unit assembly of motions 1 to 4
- a Gripping (0-90°).
- b Rotation of tongs ($\pm 180^\circ$).
- c Inclination of tongs ($+45^\circ$ - 120°).
- d Rotation of forearm ($\pm 180^\circ$).
- e Inclination of forearm ($+160^\circ$ - 50°).
- f Rotation of upper arm ($\pm 45^\circ$).
- g Inclination of upper arm ($\pm 90^\circ$).

Figure 3 — Light-capacity electrical master-slave manipulator — Typical ranges of motions for slave arms

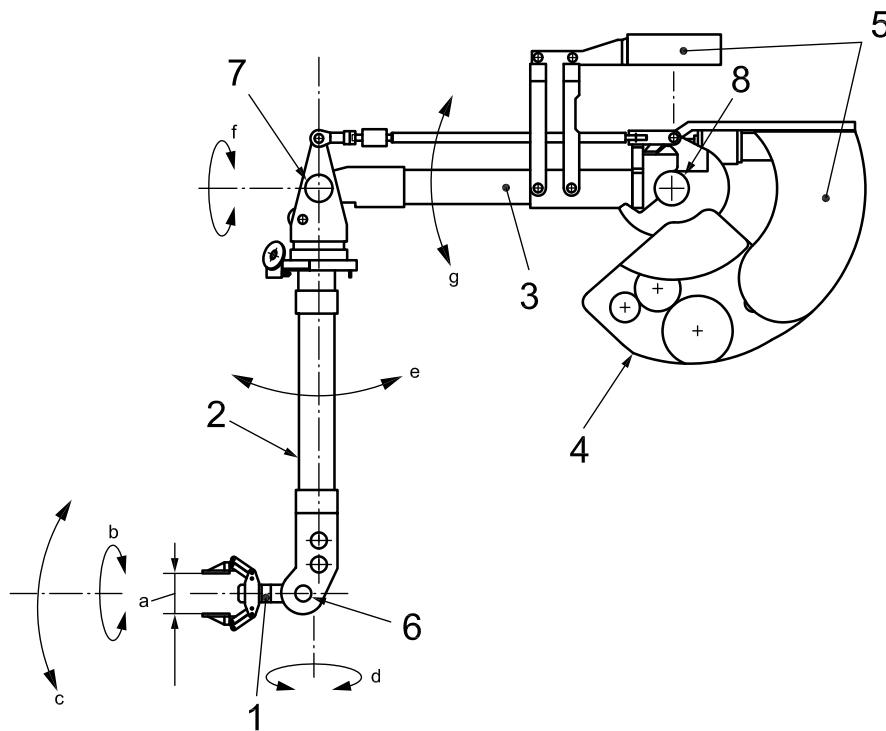
6.6.2.3 Medium-capacity electrical master-slave manipulators

For these models, the drive units are located mostly in a housing behind the shoulder pivot. As an exception, the drive unit for upper-arm rotation can be positioned at the rear of the upper arm to simplify the transmission. The positioning motions are driven by gear wheels and the orientation and gripping motions by steel cables as transmission elements inside the arm sub-assemblies. A thrust rod is often used for the inclination of the forearm. Dead-weight compensation is achieved by two counterweights (see Figure 4).

Generally, the same type of motor is used for the slave arm and the master arm for medium-capacity manipulators of class (a). For medium-capacity manipulators of class (b), different types of motors are used for the slave arm and the master arm.

Mostly two- or three-phase a.c. motors are used, in order to avoid brush friction, although with some models, d.c. motors are used. Often the drive unit type for the slave arm consists of two, three or four motors, instead of one motor, in order to reduce inertial mass.

Resolvers, incremental transmitters and potentiometers are typically used as position transducers. The motors for some types are special designs in order to reduce dimensions, weight and inertial mass.



- Key**
- | | |
|-----------------|------------------|
| 1 tongs | 5 counterweight |
| 2 forearm | 6 wrist pivot |
| 3 upper arm | 7 elbow pivot |
| 4 drive housing | 8 shoulder pivot |
-
- | | |
|---|--|
| a Gripping (0-90°). | e Inclination of forearm ($\pm 45^\circ$). |
| b Rotation of tongs ($\pm 180^\circ$). | f Rotation of upper arm ($\pm 45^\circ$). |
| c Inclination of tongs ($+50^\circ, -135^\circ$). | g Inclination of upper arm ($\pm 45^\circ$). |
| d Rotation of forearm ($\pm 180^\circ$). | |

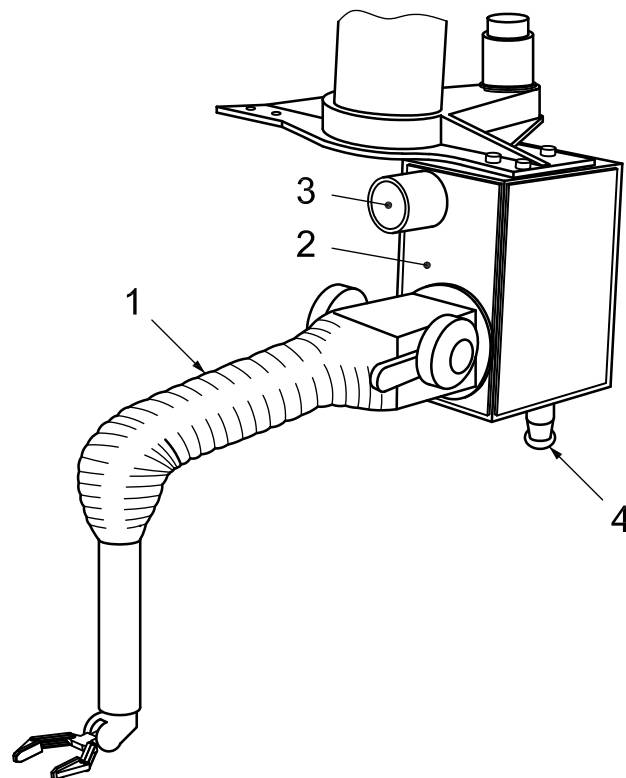
Figure 4 — Medium-capacity electrical master slave manipulator type — Typical ranges of motion travels for slave arms

6.6.2.4 Designs with special features

Some medium-capacity manipulators use gearings and steel tapes. In such designs, the backlash is essentially eliminated, but the dimensions of the drive housings are increased. To ensure protection against contamination, one or more gaiters and leaktight containment boxes for the drive units may be used (see Figure 5). With some types, steel rods are used to replace sections of the cables in order to reduce stretching under load.

Electrical dead weight compensation may be applied by adding an additional torque corresponding to the inclination of the arm sub-assemblies. This design leads to a more compact drive housing assembly with a simplified shape (see Figure 20). If the direction of the upper arm of the slave is oriented backwards with respect to the upper arm of the master, no significant difference occurs for the operator concerning the dynamics in motions, compared to a manipulator with truly isokinetic master and slave arms.

With some types, the drive housing can be tilted by a drive unit to increase the operating volume and to be able to operate overhead and vertically down with the full ranges of motion travels of the master-slave mode. If the tilting of the drive housing is provided in combination with the electrical dead weight compensation, then the tilting angle shall be taken into account in the calculation of the compensation signals.



Key

- 1 gaiter
- 2 containment box
- 3 filter
- 4 extendable viewing head for television camera

Figure 5 — Medium-capacity electrical master-slave manipulator — Typical slave arm equipped with a gaiter over elbow pivot and upper arm

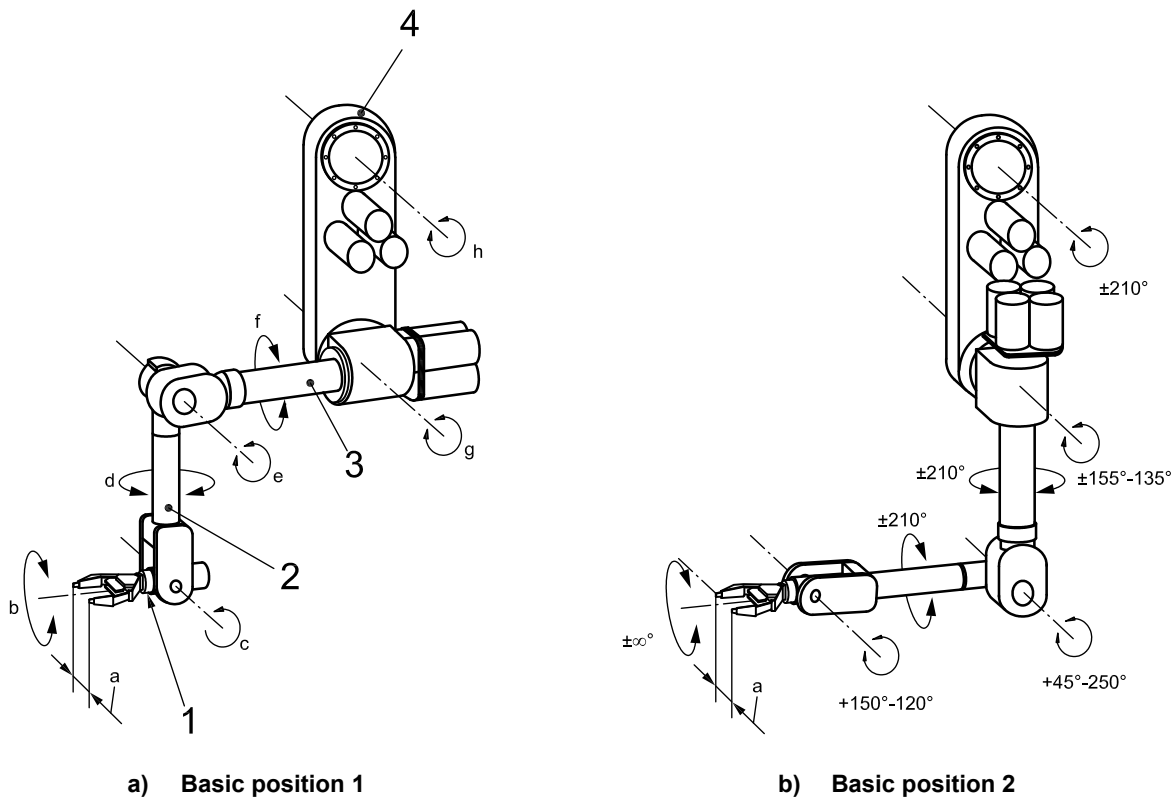
6.6.2.5 Heavy-capacity electrical master-slave manipulators

For these models, the drive units of the slave arm for inclination and rotation of upper arm are installed on the associated transmission housing behind the shoulder pivot. These motions are driven by gear wheels. The drive units for inclination of the forearm and the orientation motions are assembled behind the upper arm. Rotary shafts are used for the transmission elements in the arm. The drive unit for the gripping motion is installed behind the tongs in order to avoid a complicated transmission and hence minimize friction.

The housing is elongated like an additional arm component in order to increase the reach. This housing is inclined by an eighth drive unit (switch-operated), installed on the housing (see Figure 6).

The manipulator can begin operation from two basic positions (see Figure 6). Basic position 1 (with the forearm vertical) is well suited to working from above, the so-called “on-table situation”, while basic position 2 (with the forearm horizontal) has advantages for reaching forward into narrow spaces.

The slave arm and the master arm can be moved together from basic position 1 into basic position 2 (and reverse) by indexing.



Key

- | | |
|---------------------------------------|---|
| 1 tongs | 3 upper arm |
| 2 forearm | 4 housing with drive units |
| a Gripping (0-150°). | e Inclination of forearm (+225°, -70°). |
| b Rotation of tongs (±∞°). | f Rotation of upper arm (±210°). |
| c Inclination of tongs (+60°, -210°). | g Inclination of upper arm (+65°, -225°). |
| d Rotation of forearm (±210°). | h Inclination of housing (±210°). |

Figure 6 — Heavy-capacity electrical master-slave manipulator — Typical ranges of motions for slave arms

The kinematic system is usually optimized for basic position 1. In basic position 2, the degree of freedom, γ , (defined in Figure 2) is not matched by any single motion of the manipulator. Therefore, in basic position 2, the dexterity is restricted and to avoid this, an eighth motion with force reflection shall be provided.

Every drive unit has one a.c. three-phase motor.

All motors for the slave arm are interchangeable, except the motor for the gripping motion, which is much smaller. This pattern is repeated in the master arm where, however, all the motors and gear ratios are smaller than in the slave arm.

The four drive units in both the master and slave arms are assembled behind the upper arm in order to provide a contribution to the counterbalance of the upper arm. The rest of the dead weight is compensated electrically. Upper-arm rotation, forearm inclination, forearm rotation and hand inclination have electrical dead-weight compensation.

6.6.3 Housings, materials and surface treatment

The housings of the arm components and the drive units are made of light alloys and equipped with seals. Arm components and drive housings for slave arms of the heavy class can also be made of stainless steel, if required.

Tongs with parallel jaws are generally made of

- light alloys for light- and medium-capacity manipulators of class (a);
- stainless steel for medium-capacity manipulators of class (b) and heavy-capacity manipulators, for increased robustness.

As electrical master-slave manipulators are generally large, heavy items of equipment which are difficult to access safely, it is important to minimize the frequency of intervention for their maintenance and repair. Accordingly, the materials of component parts with exposed surfaces shall be protected against corrosion, ensuring compatibility with their function: degradation of polymer surfaces can be accelerated by ionizing radiation. All surfaces shall be designed to facilitate a high standard of decontamination. Light alloys shall be anodized. Stainless steels shall be subjected to an appropriate surface treatment, e.g. they shall be pickled and passivated. The decontamination processes envisaged shall not significantly degrade the functionality of the components, even when used repeatedly.

If different materials are bonded to one another, any contact corrosion shall be prevented by suitable measures. Organic materials shall be used to satisfy certain functions (e.g. cable installations, bearing seals, lubricants). They shall be selected on the basis of the predicted radiation fields so as to avoid significant degradation between normal maintenance intervals.

6.6.4 Ranges of motions

Motions of electrical master-slave manipulators shall have as a minimum the ranges specified in Table 2. The operating angular range of the slave arm in the main vertical plane is shown for medium (a) and (b) class manipulators in Figure 7, in which the example is designed as a pair (hence with an asymmetry in the swept operational volume as viewed from the front).

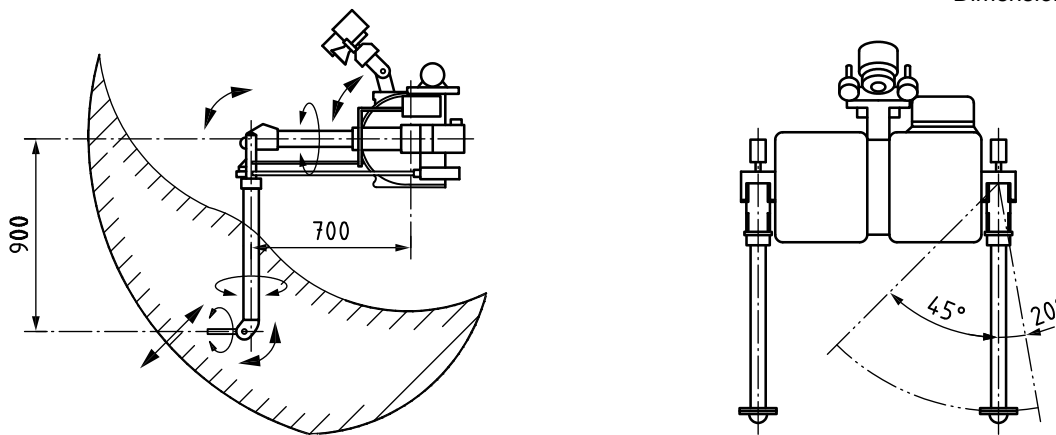
Table 2 — Ranges of motions

Angles in degrees

Parameter	Manipulator class	
	Light capacity, medium capacity (a) and (b)	Heavy capacity (basic position 1)
Inclination of upper arm	±45	+65, -225
Rotation of upper arm	±45	±210
Inclination of forearm	±45	+225; -70
Rotation of forearm	±180	± 210
Inclination of tongs	+50; -120	+60, -210
Rotation of tongs	±180	±∞
Gripping	see 6.10	see 6.10

“+” indicates away from the operator, upward or to the right.
 “-” indicates towards the operator, downward or to the left.

Dimensions in millimetres



- a) Operating ranges of motions of the slave arm in the principal vertical plane for medium (a) and (b) manipulators class (side view)
- b) Operating range for inclination of the forearm (front view), by rotation of the upper arm

NOTE 1 The ranges shown in this figure correspond to those indicated in Table 1 (arm lengths) and Table 2 (ranges of motions).

NOTE 2 In Figure 7 a), the curves refer to the wrist pivot.

NOTE 3 In Figure 7 b), a double-arm assembly, the rotational motion of the upper arms to one side is limited by the movement of the upper counterweight to 20°. In such an assembly, preserving the angular range of motion shown in Table 2 would require the width of the dual slave arm unit to be increased considerably.

Figure 7 — Ranges of motions for medium capacity (a) and (b) class electrical master-slave manipulators

6.7 Friction

Low friction values are one of the most important operational features of electrical master-slave manipulators after the load capacity. As shown in Table 3, the friction tends to rise with the load capacity as a result of design constraints. The friction is a decisive factor in the dexterity the operator can attain, and can significantly affect the amount of process work which can be done in a given time.

The forces to overcome at the handle of the master arm by the operator moving the manipulator in the no-load condition, with a force ratio between master and slave which gives a force reflection from 20 % to 25 % of the slave load, shall not exceed the values given in Table 3.

The forces to overcome at the tongs of the slave arm, when the master is driven by the slave (at the threshold of force reflection) in the no-load condition, are not allowed to exceed twice the values quoted in Table 3.

The frictional forces of the different positioning motions shall be very similar in order to allow a dextrous combination of motions. The same is true for the frictional torques of the orientation motions.

However, the values of the frictional forces perceived by the operator for the orientation motions shall be considerably lower than those for the positioning motions to facilitate guiding the manipulator.

Table 3 — Friction

Values in centinewtons

Parameter	Manipulator class				
	Light capacity	Medium capacity		Heavy capacity	
		(a)			(b)
	d.c. motors	a.c. motors	d.c. motors	a.c. motors	d.c. motors
Inclination of upper arm	120	150	500	250	400
Rotation of upper arm					
Inclination of forearm					
Rotation of forearm	80	100	300	150	200
Inclination of tongs					
Rotation of tongs					
Gripping	160	200	800	350	800

6.8 Deflection under load

When the slave arm is under load, there will be a deflection of the slave arm sub-assemblies with respect to the positions of the corresponding master arm sub-assemblies in the no-load condition.

This deflection shall be low to allow the operators to achieve an effective feeling with the force reflection. The deflections due to load are generally in the range of the values quoted in Table 4. If these values were to be exceeded significantly, the dexterity would be impaired.

Table 4 — Typical deflections due to load

Parameter	Manipulator class			
	Light capacity	Medium capacity		Heavy capacity
		(a)	(b)	
Inclination of upper arm	24 mm/10 kg	30 mm/25 kg	30 mm/45 kg	30 mm/100 kg
Rotation of upper arm	24 mm/10 kg			20 mm/100 kg
Inclination of forearm	31 mm/10 kg			30 mm/100 kg
Rotation of forearm	20°/10 kg	20°/25 kg	20°/45 kg	15°/100 kg
Inclination of tongs	10°/10 kg	10°/25 kg	10°/45 kg	10°/100 kg
Rotation of tongs	20°/10 kg	20°/25 kg	20°/45 kg	15°/100 kg
Gripping	5 mm/14,5 daN	10 mm/30 daN	10 mm/55 daN	5 mm/130 daN

6.9 Velocities

The seven motions of the electrical master-slave manipulator shall be capable of being performed in the no-load condition with values of velocity at least as large as those specified in Table 5.

With the maximum loads in the standard tongs, the velocities, which shall be attained without significant effort, shall be at least 25 % of the no-load velocities.

Table 5 — Velocities

Parameter	Manipulator class				
	Light capacity	Medium capacity			Heavy capacity
		(a)		(b)	
	d.c. motors	a.c. motors	d.c. motors	a.c. motors	d.c. motors
Inclination of upper arm, r/s	1,0	0,2	0,15	0,2	0,2
Rotation of upper arm, r/s					
Inclination of forearm, r/s					
Rotation of forearm, r/s	1,1	0,8	0,8	0,8	1,5
Inclination of tongs, r/s	1,4	1,7	1,0	1,5	1,0
Rotation of tongs, r/s	1,6	1,7	1,0	1,5	1,5
Gripping, m/s	0,25	0,8	0,5	0,8	0,8

6.10 Dimensions of tongs with parallel jaws (standard tongs)

Standard tongs have parallel moving jaws (see Figure 8). They shall be dimensioned in accordance with Table 6, corresponding to the load capacity of the slave arm.

Table 6 — Dimensions of tongs

Dimensions in millimetres

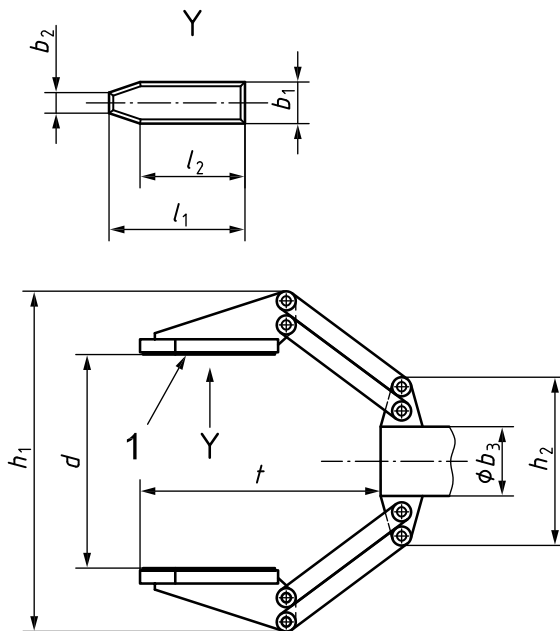
Load capacity kg	Dimensions of tongs								
	$d^{a,b}$	b_1	b_2	l_1	l_2	b_3^c	h_1^c	h_2^c	t^b
up to 24	90	18	10	55	35	40	165	107	72
between 24 and 45	120	25	14	80	53	40	225	153	90
between 45 and 100	150	35	20	125	85	120	328	240	127

NOTE For general tolerances, see ISO 2768.

^a The tongs shall be capable of being closed, i.e. to achieve $d = 0$.

^b d and t are minimum dimensions.

^c b_3 , h_1 and h_2 are maximum dimensions.



Key
1 jaw

NOTE For dimensions, see Table 6.

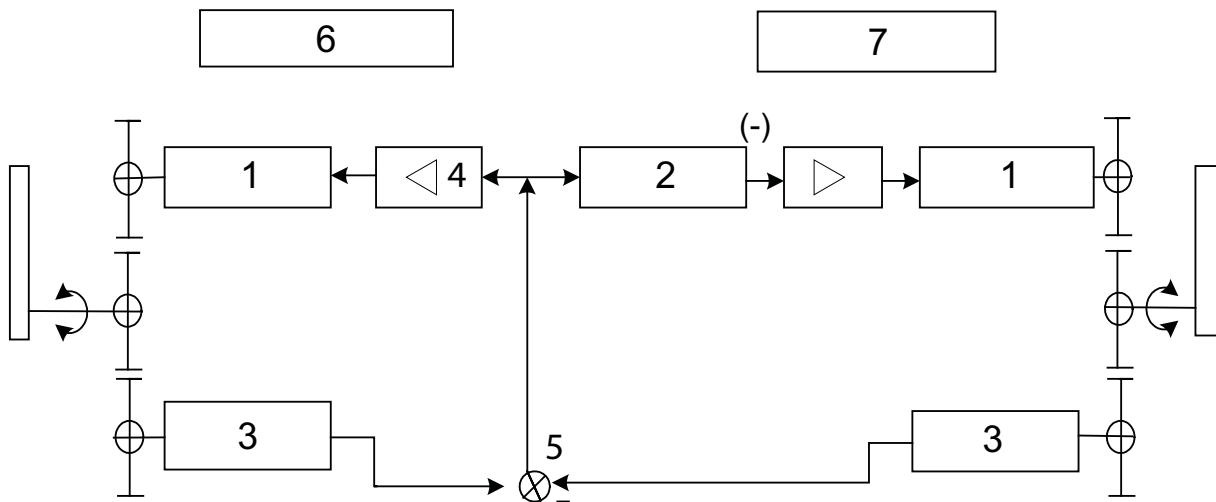
Figure 8 — Tongs with parallel jaws for general purpose

6.11 Electrical servo-system

The slave arm shall follow the motions of the master arm with an imperceptible lag to the operator. The motions of the slave arm shall be uniform (not jerky). When an object is touched by the slave arm and a force is exerted, the force reflection shall be put into action promptly (not gradually).

The block diagram of the bilateral position control circuit (very simplified) is shown in Figure 9.

When looking from the master arm to the slave arm, the control system corresponds to a conventional position control loop. However, feedback is required in electrical master-slave manipulators and is achieved as follows: a motor installed in the master arm for the corresponding slave arm component is also fed current to generate a torque opposed to the movement introduced. This torque is correspondingly stronger in the presence of a force or moment exercised or received by the slave arm, so that the operator feels pressure against his hand, proportional to the load forces at that moment.

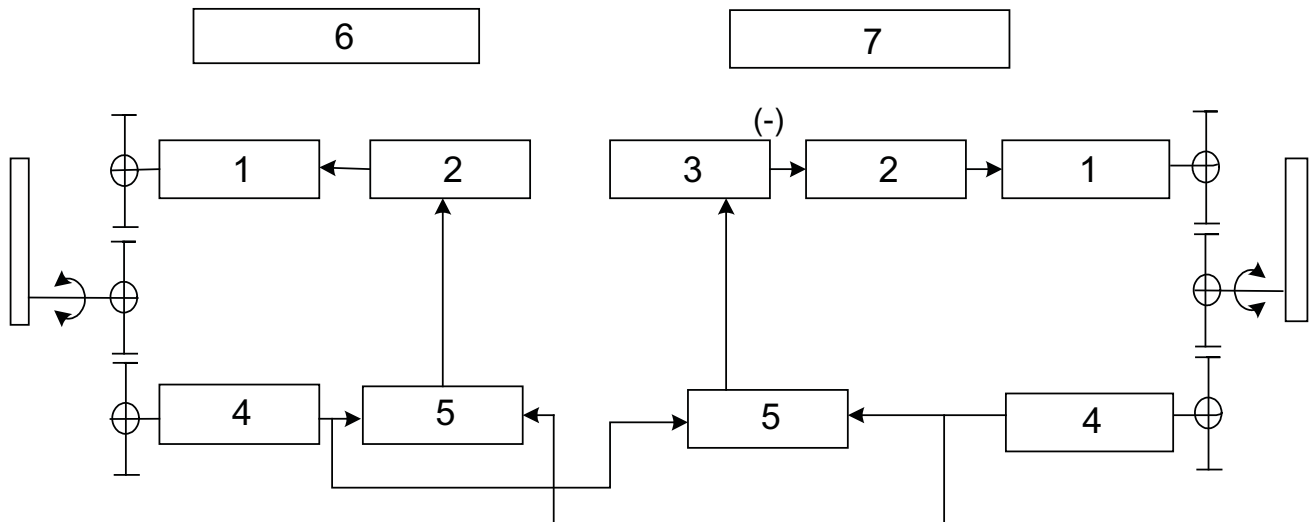


Key

- 1 motor
- 2 selector for ratio of forces in slave arm to master arm
- 3 position transducer
- 4 amplifier
- 5 comparator for set value and actual value
- 6 slave arm
- 7 master arm

Figure 9 — Bilateral position control with indirect force reflection

In order to minimize the lag between the master arm and the slave arm, additional speed signals (not shown in Figure 9) that are produced by tachometers or obtained from the position signals (see Figure 10) are generally compared. The differential speed signal is added to the differential position signal and the resultant signal is fed to the amplifier. Force reflection can be made a little indirect by assigning to the control system a certain amount of “softness”, i.e. compliance.



Key

- 1 motor
- 2 power amplifier
- 3 force ratio selector
- 4 position transducer
- 5 position control
- 6 slave arm control cabinet
- 7 master arm control cabinet

Figure 10 — Simplified function diagram of bilateral position control with separate loops for master arm and slave arm for one motion (example)

Loads on the slave arm will produce additional minor position deviations proportional to the moment induced by the load, which are still present in the state of rest. The force reflection system generates the corresponding counter-force in the master arm in the rest condition as well as during operation.

The simple control system shown in Figure 9 lends itself well to use in light-class manipulators. However, it has the disadvantage that the idling forces, mainly caused by friction and mass inertia, shall also be supported in full by the operator.

Older types of electrical master-slave manipulators were equipped with control systems using analogue electronics. If the manipulator had a remote control unit for the slave arm, separate circuits were provided for the slave arm and the master arm which, however, were cross-linked by an exchange of position signals (see Figures 10 and 13). The controllers sometimes had different characteristics for the slave arm and the master arm.

Approximately 20 years ago, the first control systems using digital processors appeared, allowing the introduction of additional features. In particular, heavy-class manipulators now have correction circuits for friction and inertial mass. In this case, it is possible to use in one drive unit one large motor instead of several small motors. Digital techniques also allow improvement of the efficiency of the power control for asynchronous motors. The simplified function diagram of such an advanced control circuit is shown in Figure 11. The schematic of the hardware enabling it, using a data bus, is shown in Figure 12.

Some control systems are equipped with optional features (see Clause 7) and with a secondary automatic work mode. A function diagram for a manipulator with an additional programmable unit for master-slave programming and play-back is given in Figure 14.

The factors of the force ratio from master arm to slave arm can be varied in steps or/and continuously between 1:1 and a value such that the operator only needs to exert 2 daN on the master arm to achieve the maximum load of the slave arm. Operations are generally carried out with force amplification, so some models have as the smallest force ratio 1:2, and not 1:1. With medium-heavy and heavy manipulators, force ratios of around 1:4 are preferred, giving 20 % to 25 % force reflection of the maximum load capacity.

Concerning the force reflection, it is more important for the operator to feel when the slave arm contacts an object, i.e. to perceive a noticeable change in the force, than to feel the absolute magnitude of the force. The operation of the electrical servo-system shall be as simple as possible. The operator shall be able to come into the master-slave work mode with very few operating steps. However, in the general situation, before beginning operation, the components of the master arm are not in synchronous orientation with respect to the corresponding components of the slave arm. A “start mode” is therefore necessary, in which the master arm components are slowly moved into the orientations of the slave arm components. When synchronous orientations of the slave and the master components are achieved, the slave brakes can be released, the control loops closed and the work started.

NOTE 1 Because of the operational advantages, bilateral position controls are generally provided.

NOTE 2 Control circuits with force feedback can be realized in alternative ways, e.g. as follows:

- position control for the slave arm and indirect force control (motor currents) for the master arm;
- position control for the slave arm and force control for the master arm, using sensors on the master arm and slave arm.

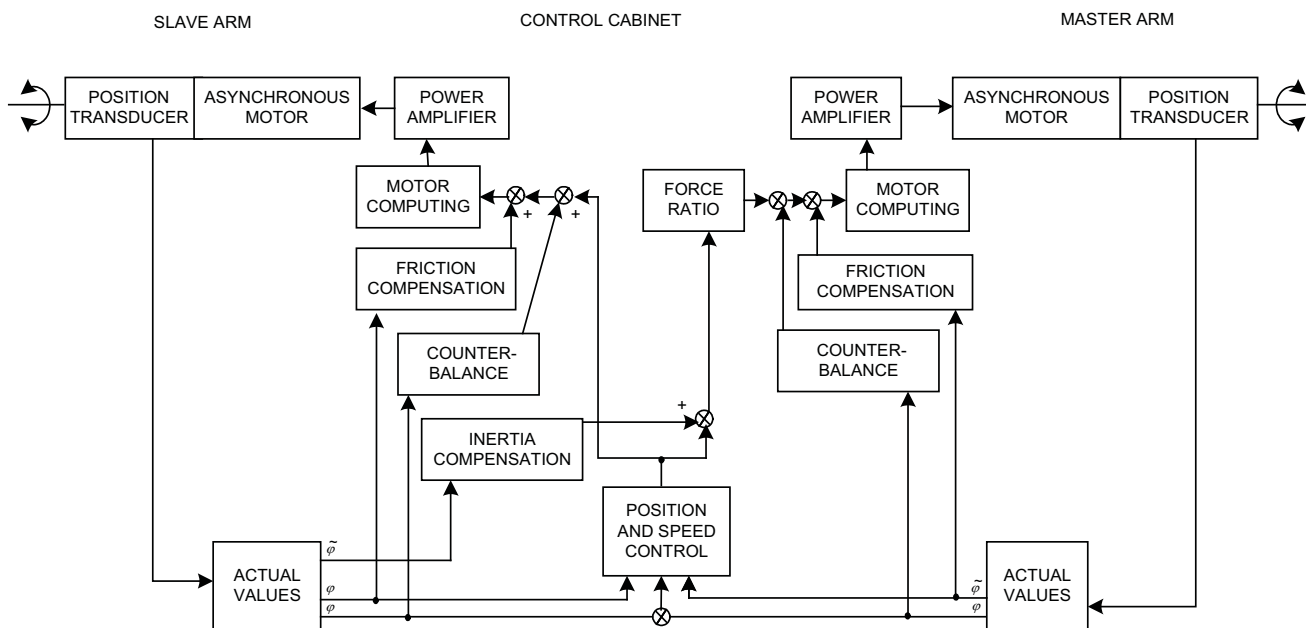


Figure 11 — Heavy-capacity electrical master-slave manipulator — Simplified function diagram of the bilateral position control for one positioning motion (example)

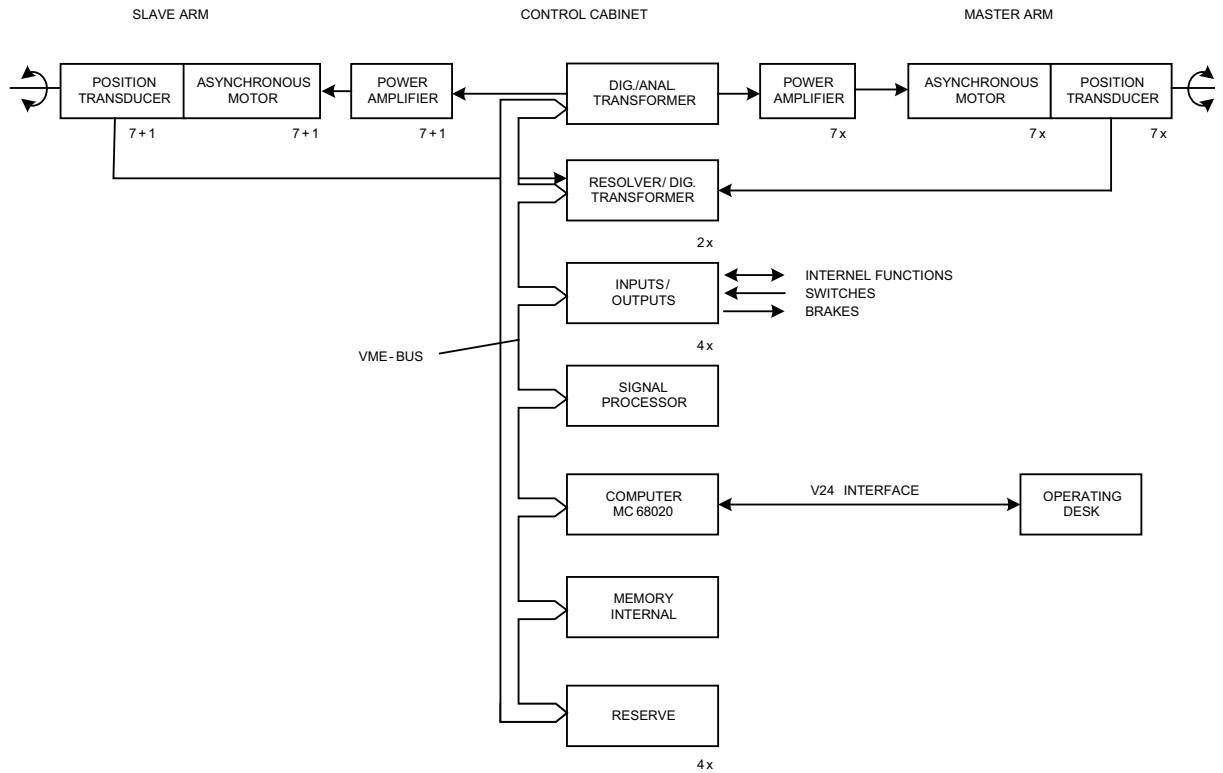


Figure 12 — Electrical master slave manipulator — Hardware schematic (example)

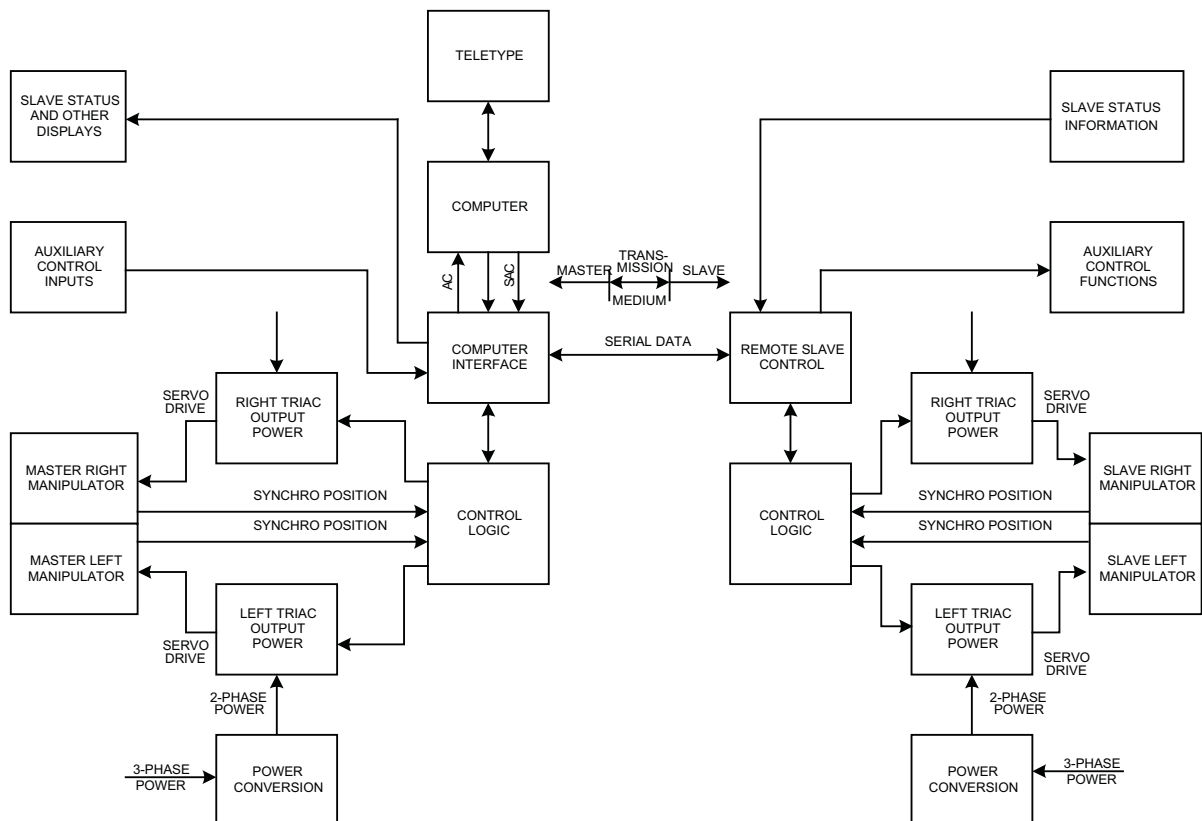


Figure 13 — Minicomputer servo-system with remote control unit for two manipulators (example)

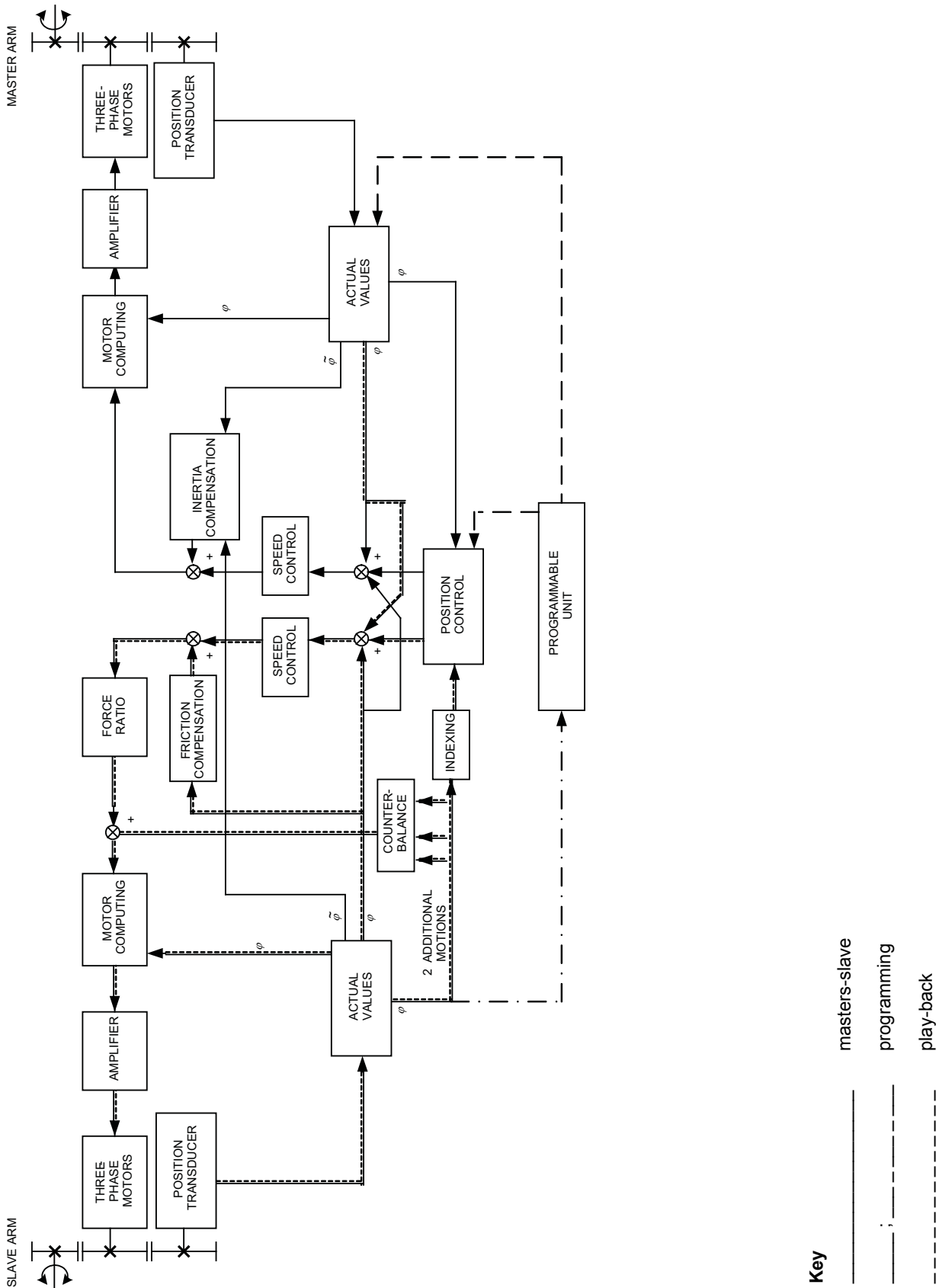


Figure 14 — Medium-capacity electrical master-slave manipulator — Simplified function diagram of the bilateral position control, with additional programming and play-back mode (example)

7 Optional features

Digital control systems and additional components allow a variety of optional features. The following may be available depending on the model:

- a) indexing of arm motions, especially the motions of the upper-arm and forearm inclination and, with heavy-class manipulators, all the other motions including continuous hand rotation:
 - indexing realizes a large motion travel of the slave arm, while retaining the master arm in positions convenient for the operator;
 - indexing can be obtained either by moving the slave arm via operating a set of indexing switches, or by moving the master arm after uncoupling the control loop with a switch that also locks the slave arm;
- b) by scaling, the travel ratio between the master and the slave arm can be adjusted to various proportions (e.g. 1:2 or 2:1);
- c) automatic limitations can be applied to forces and torques (e.g. for handling delicate objects);
- d) force ratio of master arm to slave arm may be adjusted to values above 1:1 (e.g. 2:1) (to obtain more sensitivity);
- e) braking of one or several motions (for more precise movements of other motions);
- f) blocking by software of a part of the travel range of one or several motions (to prevent collisions);
- g) collision avoidance between the slave arms of a pair;
- h) compensation of the weight of tools or objects held in the tongs;
- i) moving into the basic position(s) (after indexing);
- j) moving back into a position which has been previously stored (slave arm and master arm together);
- k) automatic work mode (secondary control mode);
- l) point-to-point control, also with linear interpolation; programming with speed control by operating devices like power manipulators via or by a PC;
- m) path control with teaching, programming by the master arm and subsequent play-back (e.g. for exchange of tools).

NOTE 1 A motorized arm can only be optimized in its design to work in one working mode: master-slave or automatic (low-friction or accurate positioning). As a consequence, controlling a slave manipulator with a programmable unit will not provide the positioning accuracy of an industrial robot, just as using an industrial robot as a slave arm will not provide satisfactory force-reflection performance.

NOTE 2 Automatic work on objects is problematical. The positions and orientations of the objects need to be known, and the required accuracy needs to be low. The time for programming will be relatively long; therefore the frequency of repetition needs to be large enough to justify the resource commitment.

For other components of the manipulator system, additional optional functions can be realized, e.g.:

- TV camera tracking, i.e. automatic movement of the camera (e.g. by the movement of its swivel-tilting head), so that the image of the tongs remains centrally on the monitor screen while the slave arm is moved in a wide range;
- blocking by software a part of the working volume in order to facilitate access of the transporter.

NOTE 3 It is important to consider carefully such optional functions, which can be important for the intended applications, in order to avoid operation of the manipulator becoming overly complicated.

NOTE 4 The compensation of the weight of tools has proved to be the most important and useful of the optional features of electrical master-slave manipulators.

8 Operation

8.1 Master arm

Master arms are dimensioned in accordance with the motion limits of the human arm. It is possible (and often advantageous) to use one type of master arm for slave arms of different load capacity, even though, unlike in small-capacity manipulators, the slave arms of medium- and heavy-capacity manipulators are generally longer than the master arm. For a length ratio of master arm to slave arm of up to 1:1,5 maximum, this effect is essentially imperceptible to the operators (see Figure 15). Nevertheless, the accuracy of positioning decreases with greater length ratios.

The range over which a human being can recognize changes of magnitude of force is ≈ 200 cN to $\approx 4\,000$ cN. This shall be taken into account in the design (including the dimensioning) of the master arm. Other components of the manipulator system may also be provided with optional functions.

The master arm is designed for a lower load capacity than the slave arm, typically 10 daN, including some reserve and safety margins. The types of drive unit for the master arm consist of either one motor or, in order to reduce the inertial mass, two motors.

The gear ratio of the master drive unit type is smaller than that of the slave drive unit type, in order to reduce inertial mass and friction. Some types of manipulators have master arms with steel tapes as transmission elements. These decrease the friction, but increase the dimensions of the drive housing. In contrast to steel cables, tapes should run in one plane.

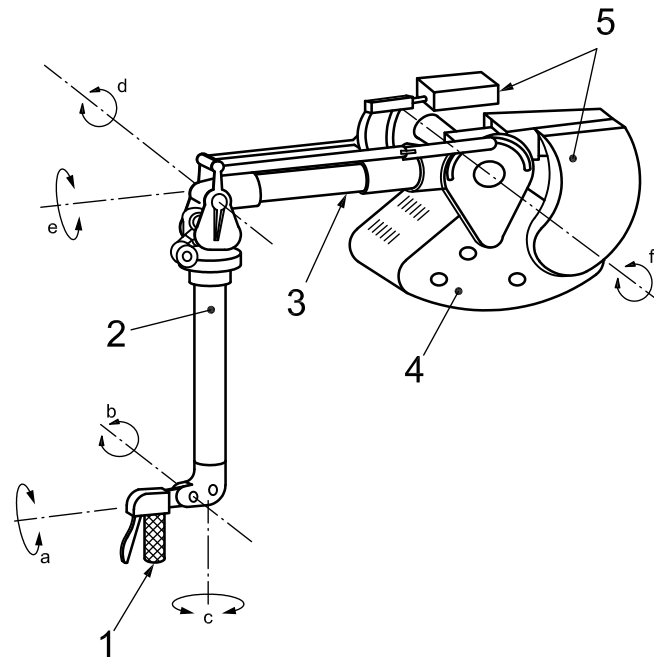
The master arm is in most cases equipped with a so-called pistol handle (see Figure 15) although in some types, a squeeze handle is used. For very precise control of the movements, with some types, an additional grip for the left hand is mounted at the left or front side of the pistol handle.

A special switch shall be integrated into the handle with the following function: if the operator takes the handle, the manipulator is connected in master-slave mode, but if the handle is released, all motions of the slave arm and master arm are immediately braked.

The switches for indexing (see Clause 7) shall be arranged at the handle. With light-class manipulators, the master arm and the slave arm are identical, except for handle and tongs respectively. With heavy-class manipulators, the master arm shall also have rotary shafts as transmission elements to be changed from basic position 1 into 2 (and reverse) by indexing.

The simplified variant of "heavy" capacity manipulators, which has a slave arm with rotary shafts as transmission elements, is generally operated by a master arm with steel cables as transmission elements. As for the "medium" capacity manipulators, the friction effect is therefore reduced.

One operator can readily control a pair of light and medium manipulators, but heavy-capacity manipulators normally require one operator each.

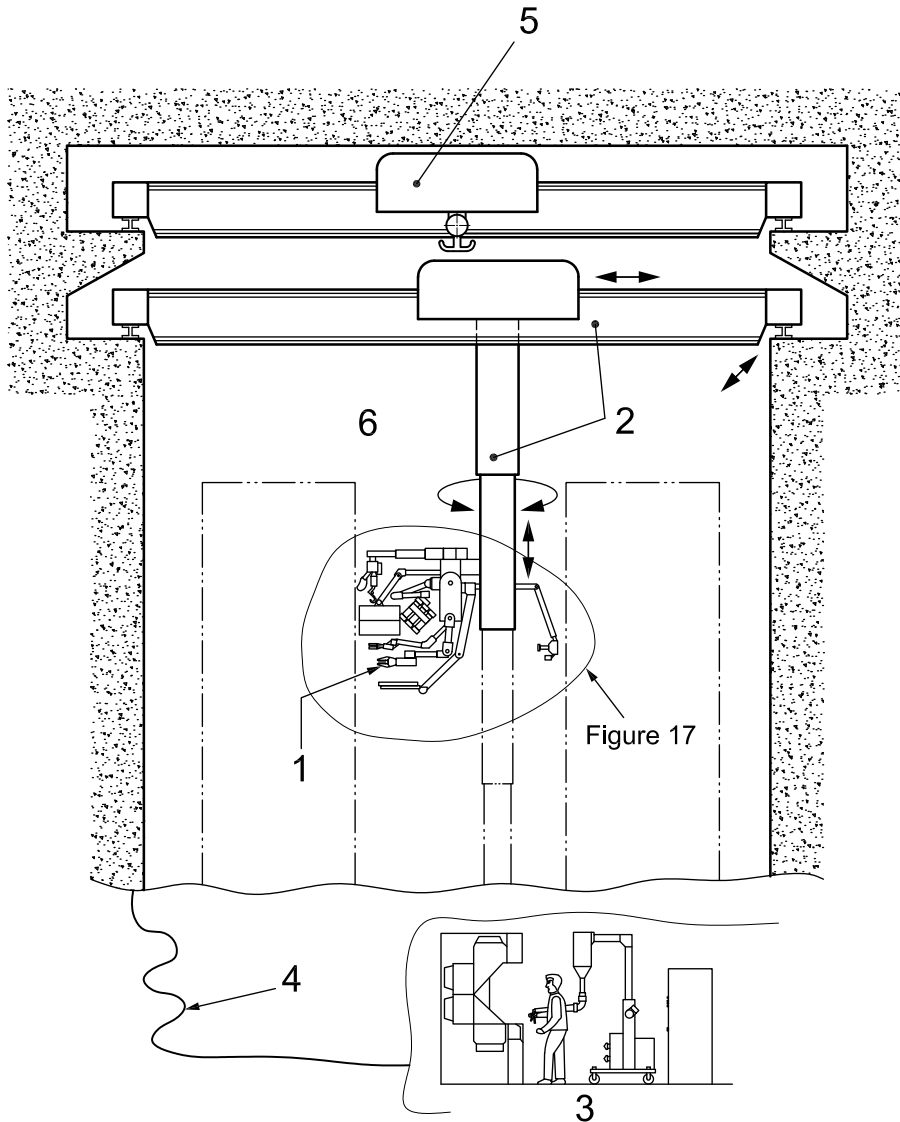
**Key**

- 1 handle (pistol type)
- 2 forearm
- 3 upper arm
- 4 drive housing
- 5 counterweight
- a Rotation of handle ($\pm 180^\circ$).
- b Rotation of wrist joint ($+60^\circ$, -120°).
- c Rotation of forearm ($\pm 180^\circ$).
- d Inclination of forearm ($\pm 45^\circ$).
- e Rotation of upper arm ($\pm 45^\circ$).
- f Inclination of upper arm ($\pm 45^\circ$).

Figure 15 — Master arm for medium/heavy-capacity class model (example)

8.2 Operating station

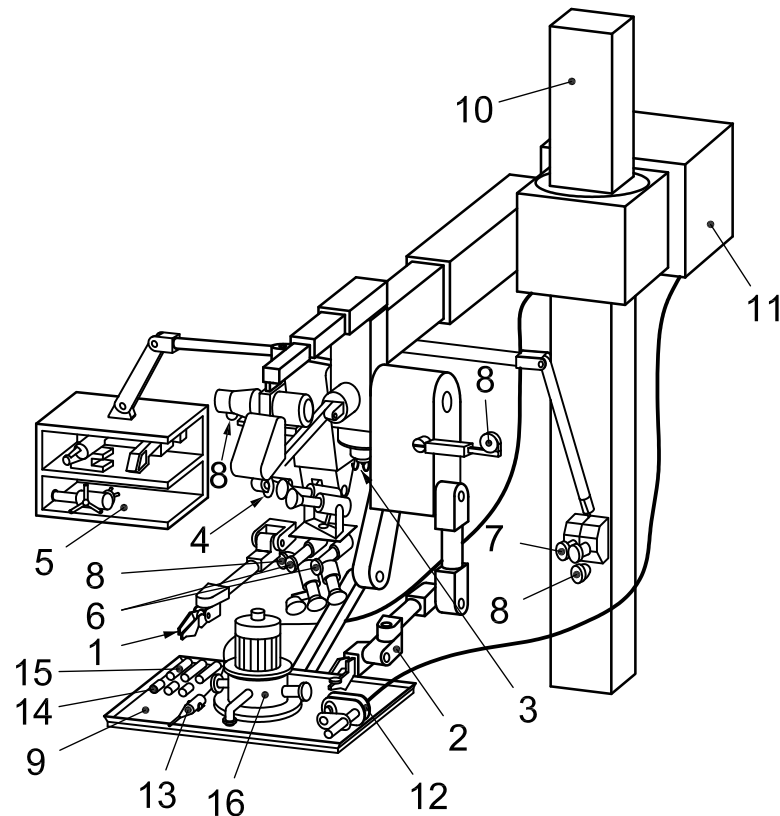
The operating station for applications where only TV systems are used for observation can be located some distance from the hot cell (see Figure 16). It typically consists of two master arms, an operating desk, control cabinets and a set of TV monitors (see Annex B). The operator can stand or sit. Standing, he can step forwards, sideways and backwards and so avoid the necessity for some indexing motions, if moderately long reach is required.



Key

- 1 manipulator unit (slave unit)
- 2 transporter
- 3 control station
- 4 transmission system
- 5 crane (e.g. 20 t)
- 6 hot cell

Figure 16 — Remote handling system for maintenance in large hot cells, with two electrical master-slave manipulators, bridge transporter and TV systems (example)

**Key**

1 medium-capacity slave arm 45 kg	7 stereo camera (overall view)	12 welding machine
2 heavy-capacity slave arm 100 kg	8 searchlight	13 protective gas jet
3 driven double-grip hook	9 working platform	14 plug of paper
4 auxiliary crane	10 mast of the transporter	15 pipe piece to be welded
5 tool magazine	11 welding control unit	16 new component (workpiece)
6 stereo TV camera (workplace observation)		

Figure 17 — Slave unit equipped for exchange of a process component with welded pipe connections (example)

In principle, a TV-only system of this kind can be operated by one person, but generally only for short, occasional tasks. More extensive work of this type requires a team of several persons. Such a team might typically consist of seven people:

- two operators for the right and left manipulators,
- one operator each for the transporter, the crane and the TV cameras,
- one person for work planning, task supervision and documentation, and
- the leader.

In a hot cell equipped with shielding windows, the master arms are generally mounted on an overhead carriage so that they can be moved from one window to another (see Figure 20). The master station then consists of the two master arms, an operating console and control cabinets.

Transmission of signals and power is generally made by multicore cables (see Figure 16 and Figure 20). Care shall be taken in the design to ensure adequate reeling or control of cable routes, lifetime of the cables and (where necessary) remotely disconnectable plugs and socket systems, which shall be compatible with the anticipated levels of dust, contamination, etc.

For interventions and maintenance tasks in hot cells, where no manipulators are permanently installed, the master station shall be mobile. For manipulator vehicles (see Figure 21), the master station may be installed in a small truck. The control can also be made via radio, if the vehicle has storage batteries on board, to get longer “reach” and more flexibility concerning the environmental with regard to conditions. The master station can also be located at a distance of many kilometres from the work area.

9 Slave units and transporters

Two electrical master-slave manipulator slave arms are often installed as a pair in order to increase the dexterity and the load capacity of the system (see Figure 18). Together with TV cameras and auxiliary equipment, they comprise the slave “unit” (see Figures 16 and 17).

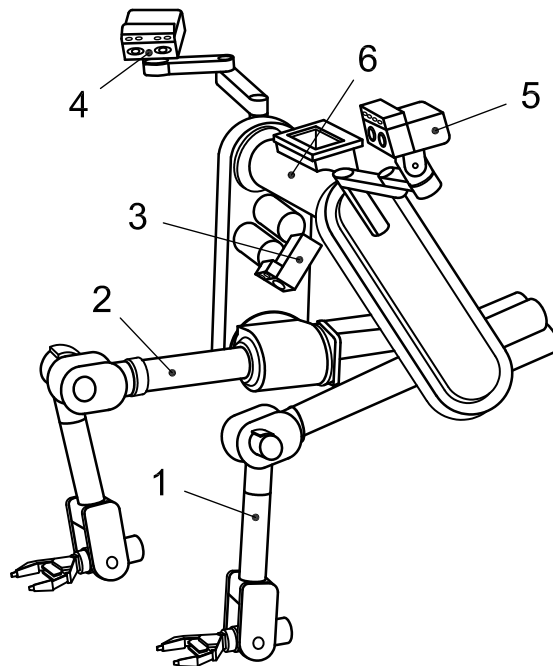
The transporters typically have four additional switch-operated motions (X, Y, Z and γ). They are similar to those of power manipulators, standardized in ISO 17874-4.

The preferred transporter design for large hot cells consists of a moveable bridge on rails, a cross-travel carriage and a vertical multiple telescope with a hoist. In addition, the slave unit can be provided with a swivel motion (see Figure 16).

NOTE ISO 17874-4:2006, notably its Annex A, provides more requirements and information, specifically for surface treatment, housings, safety, electrical equipment, operating devices and control systems.

The slave arms shown in Figure 17 are moved into basic position 2 by indexing, because in this kind of application, it is necessary to reach deep into narrow spaces. On the right-hand side, a medium slave arm of class (b) is shown for more complicated work, and on the left-hand side, a heavy slave arm for heavy objects. To be able to work independently for a longer time at large distances from transfer ports, the slave unit is equipped not only with TV cameras for work observation, but also with an auxiliary crane, a tool magazine, a working platform and a TV camera for survey (following the concept of the mobile working station) (see Figure 17).

For more on TV systems, see Annex B.



- Key**
- | | | |
|-------------------|---------------------------------------|--------------------------------------|
| 1 left slave arm | 3 central TV camera | 5 left 3D camera on articulated boom |
| 2 right slave arm | 4 right 3D camera on articulated boom | 6 shoulder assembly |

Figure 18 — Unit with two slave arms (heavy capacity) and TV cameras (example)

As an adjunct for the manipulator unit, a heavy remotely operated bridge crane, for example with a load capacity of 20 t and an auxiliary hoist of 2 t, is often installed for lifting and transportation of heavy loads (see Figure 16).

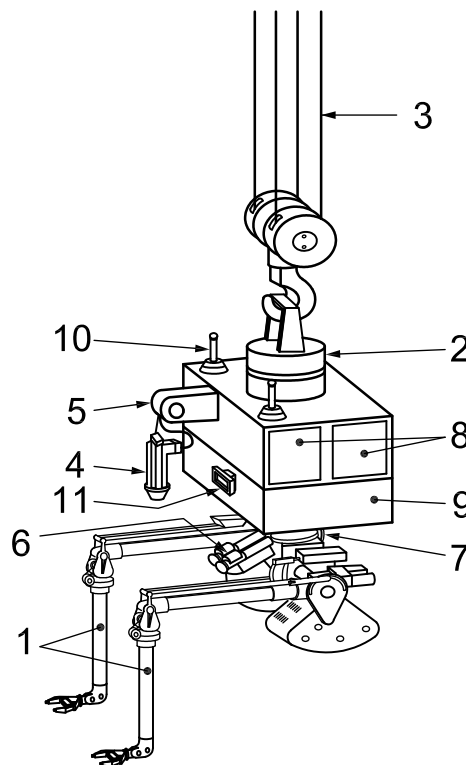
A bridge crane with two cable loops (see Figure 19), e.g. in a hall, can be also used as the transporter for a two-armed slave unit. With this solution, there are some restrictions concerning the work capability because of the flexibility of the wire ropes: if a high force has to be applied in one slave arm, the other slave arm shall be clamped on an object. Typical applications are maintenance and decommissioning. If such a slave unit includes storage batteries, the control can be achieved via radio and complicated cable handling is avoided (an arrangement sometimes known as a “flying” slave).

A variant for hot cells with shielding windows is shown in Figure 20. For such an application, the upper arms of the slave arms are orientated backwards in order to be able to work near the windows in the viewing direction of the operator. On the slave carriage, an auxiliary crane is installed. The slave and master arms shown here belong to the medium-capacity manipulators of class (b) and have electrical dead-weight compensation.

To facilitate operation of the slave unit, a bridge crane may be provided.

Transporters on rails can also have different designs, e.g. a mast instead of a telescope with a vertical moveable slave unit, moveable mountings on a sidewall with a boom, moveable portals on the floor, vehicle with a truck loading crane, etc.

A slave arm of a heavy- or medium-capacity manipulator of class (b) can replace a medium-power manipulator. For that purpose, the slave arm can be mounted for example on the power manipulator transporter.



Key

1	slave arms	5	hoist for tool	9	storage batteries
2	swivel unit	6	stereo TV camera	10	aerial
3	rope of the crane	7	swivel tilting unit for cameras	11	lamp
4	tool	8	control units and senders		

Figure 19 — Slave unit on a crane as transporter (example)

When complicated work has to be done for only a short time, a heavy-power manipulator can be used to transport a slave arm to the workplace like a large tool. With a special type of transporter for interventions in hot cells, the slave arm is lowered into the hot cell through a transfer hole in the cell ceiling from a sealed container. This type of system can be used for maintenance, conversion of hot-cell equipment or decommissioning.

For use inside buildings or in the open air, slave arms of electrical master-slave manipulators can also be installed on vehicles, which can be moved independently on the ground (see Figure 21 and ISO 17874-4:2006, Clause 7). Other transport solutions include the use of a fork lift truck or a tracked excavator. If the vehicle has energy storage on board, remote control can be arranged via radio.

10 Special tongs and tools

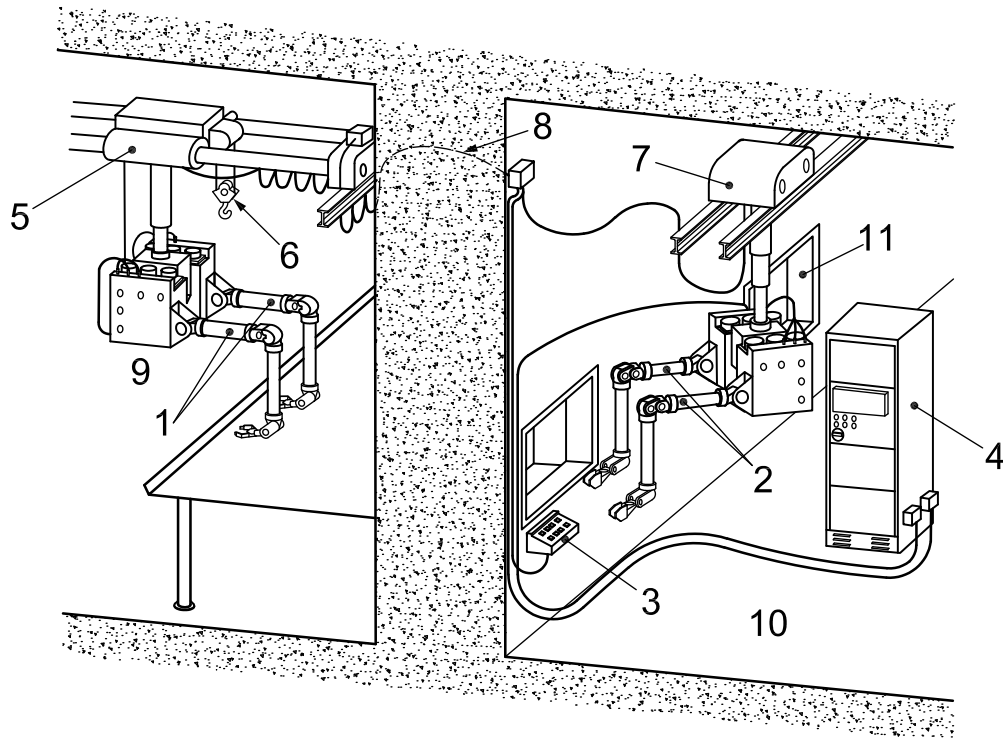
Electrical master-slave manipulators can be fitted with special tongs and tools, including the following:

- a) special tongs:
 - 1) tongs with parallel jaws for gripping hollow workpieces from the inside;
 - 2) jaws of different sizes and with special shapes;
- b) second end effector:
 - 1) lifting hook, mounted near the shoulder or wrist pivot;
- c) tools adapted for gripping by the standard tongs, such as:
 - 1) electric tools: impact wrench, disk saw, bow saw, parting-off grinder (e.g. with diamond disc), drilling machine (e.g. with crown drill), nibbler;
 - 2) hydraulic shears, metal sheet-breaker;
 - 3) mechanical tools: tool adapter for socket wrenches (e.g. with ratchet), various tools;
 - 4) thermal tools: flame cutting torch, plasma cutting torch, shielded arc welding torch, sheathed electrode holder for electric welding;
 - 5) tools for concrete: electric chisel, percussion drilling machine, compressed-air chisel;
 - 6) auxiliary equipment: spray device for fixing contamination, radiation measuring device.

Electrical master-slave manipulators are especially suited to the deployment of tools which shall be guided along a path.

NOTE 1 Nearly all tools can be adapted, if the combination of tool and adapter does not exceed the limits of load capacity and reaction forces and torques of the manipulator.

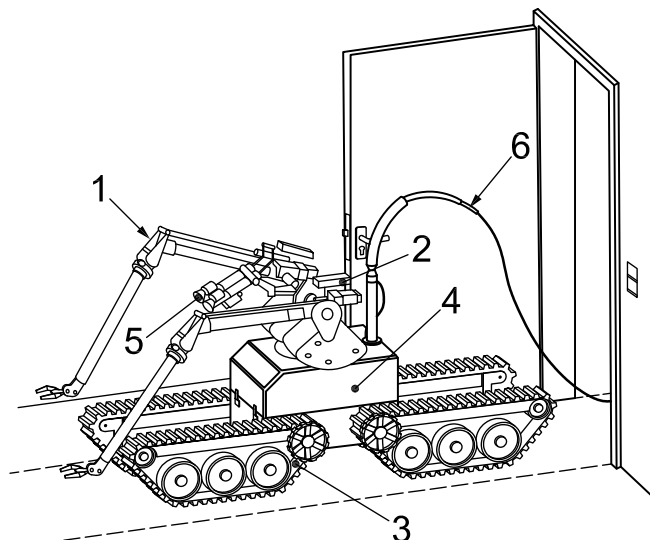
NOTE 2 If the weight of a tool exceeds the load capacity of the slave arm, it can be applied while hanging on a balancer hoist, which automatically compensates the weight of the tool.



Key

- | | | |
|---------------------|-----------------------|---------------------|
| 1 slave arms | 5 slave transporter | 9 hot cell |
| 2 master arms | 6 auxiliary crane 1 t | 10 operating area |
| 3 operating console | 7 master transporter | 11 shielding window |
| 4 control cabinet | 8 transmission cable | |

Figure 20 — Two electrical master-slave manipulators, with transporters, for hot cells with shielding windows (example)



Key

- | | | |
|------------------|---------------|-------------------------------|
| 1 slave arm | 3 chassis | 5 3D camera |
| 2 swivel, turret | 4 control box | 6 cable for power and control |

Figure 21 — Two slave arms of electrical master-slave manipulators on a small vehicle (example)

11 Criteria for selection

The main criterion for the selection of an electrical master-slave manipulator is the required load capacity. Secondary considerations depending on the application, such as restrictions of the permissible dimensions or the weight of the slave arm, can also reduce the number of suitable models.

If complicated tasks or a wide variety of tasks need to be carried out, a pair of master-slave manipulators should be used. For medium-sized hot cells, medium-capacity manipulators are generally the correct models to select. For large hot cells, production facilities and maintenance work, manipulators of medium capacity, class (b), are recommended.

Small remotely controlled vehicles can only effectively be equipped with two manipulators of light or medium capacity, class (a), or with a single manipulator of medium capacity, class (b).

Heavy-capacity manipulators are designed for maintenance in large hot cells and for decommissioning. They are especially suitable to the deployment of powerful tools.

12 Testing

Electrical master-slave manipulators shall be tested before commissioning (acceptance testing) and during their operation time (with inspections and tests scheduled at regular intervals).

For testing, see ISO 17874-4, and for measurements of no-load forces and torques, see ISO 17874-2:2004, Annex A.

13 Non-radioactive trial cells

Considerable improvements in working efficiency can be achieved if a non-radioactive trial cell is used. This can address such issues as:

- operator training, including virtual reality techniques;
- manipulator system capability;
- error and fault avoidance;
- reliability assessments and maintenance planning;
- positions, types and number of TV cameras to be used for satisfactory observation of the works.

For details, see ISO 17874-4.

Annex A (informative)

Features of prototypes and experimental devices not covered by this part of ISO 17874

A.1 General

This annex outlines certain features of prototypes and experimental devices which are not covered by this part of ISO 17874.

A.2 Arm structure

- a) Nine motions including four pivots. Such an arm is able to reach around objects and combines the advantages of the elbow-up and elbow-down structures.
- b) Eight motions with a fourth positioning motion. The upper arm can additionally be inclined in the direction of the X axis, enabling it to reach around objects by this otherwise redundant motion.
- c) Eight motions with a fourth orientation motion (swivelling of tongs). Such an arm is able to match (after indexing) the requirements for multipurpose remote handling devices (see ISO 17874-1:2010, Clause 5) in both the elbow-up and elbow-down situations.
- d) Horizontal forearm and vertical upper arm. Such an arm can reach deep into process structures where the space is narrow.
- e) Telescopic arm with two pivots. The arm is similar to the arm of a mechanical master-slave manipulator with telescopic arms.
- f) Horizontal forearm and horizontal upper arm. The arm can be bent in the horizontal plane.
- g) Suitable for use under water. There are two approaches: the drive housing and the arm sub-assemblies of the slave arm can be sealed, or else only the drive housing is sealed and the arm sub-assemblies are flooded.

A.3 Drives

Hydraulic drives including rotary motors, angle positioners and piston cylinders.

A.4 Design

Two drive units for inclination and rotation, coupled at the elbow and shoulder as usually arranged at the wrist. Either the load capacity can be increased or the necessary torque of the motors can be decreased by this design approach.

Drive units for the orientation motions and for gripping located in the forearm. The transmission of motions and torques is simpler, but the weight of the forearm becomes much higher in this design option.

A.5 End effectors

Tongs with more than one motion:

- two fingers which can be articulated at additional joints, e.g. with three pivots which are not independent;
- tongs with three, four or five fingers.

A.6 Master arm

- a) Exoskeleton master controller. This is a structure which is fastened on the forearm and upper arm of the operator. Not only the motions of the hand, but also of the whole arm of the operator, are transferred to the manipulator. A potential problem is that during extended operation periods, high concentration shall be sustained by the operator to avoid motions which are not intended. The operator cannot simply release the master controller for casual purposes and a second person is needed to fasten the exoskeleton. The operator is not able to execute secondary activities at all if he works with two manipulators of this type.
- b) Master controller like a sleeve into which the operator puts his arm.
- c) Mini-master with length, for example of 1/5 or 1/10 of the slave arm. Such a master controller needs much less space, but the positioning accuracy of the slave is significantly reduced.
- d) Master controller with a telescopic arm. In height, less space is needed. If the slave arm is an articulated one, the control computer shall execute a transformation of the coordinates.
- e) The handle of a master controller in a Cardanic arrangement (pivoted rings). The orthogonal three axes (α , β , γ) of the wrist meet in one point. This is the ideal approach to meet the requirements for multiple remote handling devices corresponding to ISO 17874-1:2010, Clause 5, concerning the orientation motions.

Annex B (informative)

Television systems

Experience over several decades of remote handling systems used in nuclear applications, such as post-irradiation examination, fuel reprocessing, plant maintenance and decommissioning, has explored a wide range of design options and developed a set of general operational preferences, including those for visual monitoring of the tasks carried out. This annex summarizes these general preferences, as guidance for consideration by remote handling systems designers.

The use of TV systems as the only or principle visual monitoring devices for remote handling operations requires a minimum of two cameras for safety and working efficiency: one for viewing the work point directly and one to show the manipulator in its working environment (i.e. the relationship to other equipment, any trailing cables connected to the manipulator or its tools, etc.). In-cell lighting needs to be provided with adequate illumination intensity at all points to be viewed, appropriate spectral distribution for the types of cameras intended and absence of strobing which might beat with the framing rate of the cameras. The display screens should be sited so that they can be viewed by the operator(s) without any visible glare reflected in them from windows or lighting fixtures.

In particular, when a limited number of cameras is deployed, they should be equipped with remotely adjustable orientation, zoom and focus controls, and preferably be colour cameras and of high resolution, for optimum image content differentiation. The zoom lens should include a wide-angle capability.

In most cases, to get an impression of the relative distances of objects and the manipulator components including the end effector, orthogonal views with two cameras are used. Three typical arrangements are as follows:

- one camera looks horizontally towards the object and the second one views at a right angle from the right or left side;
- two cameras look from the upper left and upper right with a right-angle between their directions;
- one camera looks horizontally straight ahead and the second one vertically from above.

In addition, it can be beneficial to the operators to have a camera mounted on the forearm of each manipulator, viewing the working zone at the tongs or end effector.

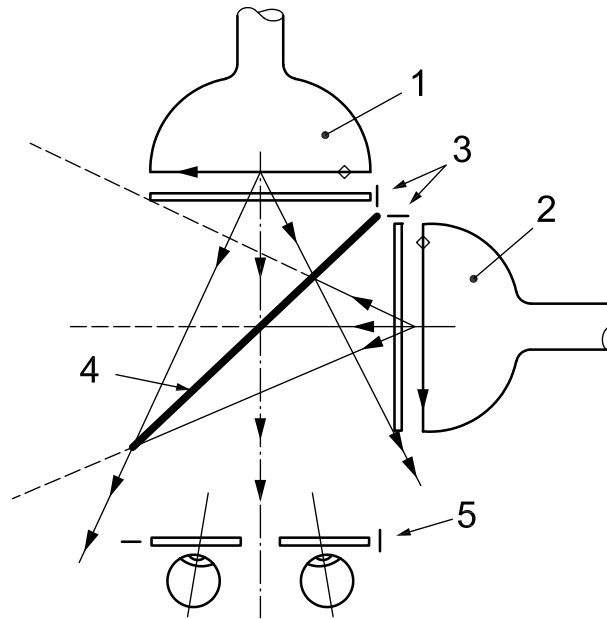
Better information concerning the relative distances of the various objects in view may be obtained by the operator using stereo TV with two cameras, typically separated by a distance a little wider than human eyes. There are many methods of producing stereo or pseudo-stereo images. The best results can be obtained by the method of orthogonally polarized light or by left-right alternated shutter spectacles used in conjunction with a 100 Hz monitor displaying alternately the left and right views. High-quality cameras are necessary to obtain satisfactory images. Studies have found that experienced operators usually prefer multiple orthogonal 2D views and that prolonged use of 3D systems can be mentally wearing. However, for short tasks or in situations where multiple cameras are impracticable to deploy (e.g. on remotely operated vehicles or rarely maintained structures), the intrinsic advantages of a well-designed 3D system are likely to be of benefit.

The TV cameras are mounted on swivel-tilt heads or articulated booms. Some slave-arm models have a TV camera installed in the drive housing with a lens system which can be driven out of the lower surface of the housing.

TV systems can also be used to complement direct views into a hot cell via shielding windows.

All objects and working points shall be clearly visible, in addition to the various parts of the remote handling devices, in order to be able to assign distances and directions to objects, if the work in large hot cells is to be efficient and safe. To ensure this, a number of TV cameras shall be installed on the manipulator unit, on the remotely operated crane and at fixed points in the hot cell. Optionally, TV cameras can be used at different locations, which can be set down and oriented by a slave arm if needed.

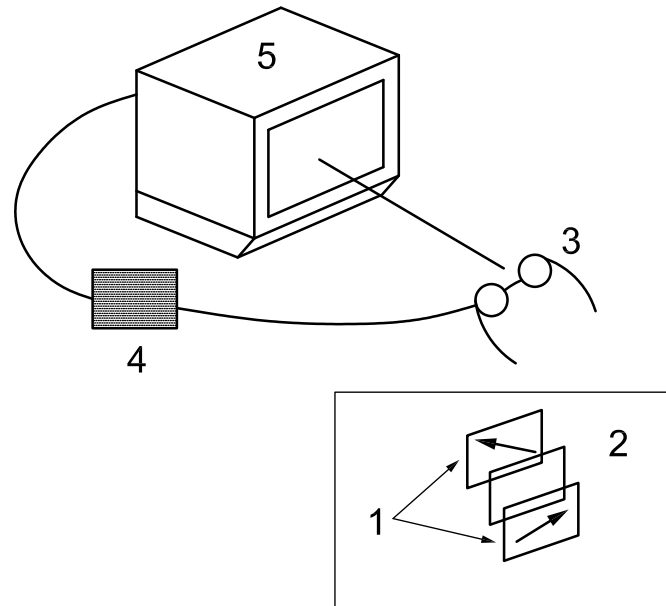
There are likely to be many tens of TV cameras used in a single complex system. However, the images of all the TV cameras do not need to be visible at the same time. Therefore, the number of TV monitors in the operating station is likely to be much smaller but can still amount to ≈ 20 .



Key

- 1 monitor for left TV camera
- 2 monitor for right TV camera
- 3 orthogonal Polarization filters
- 4 semi-reflective mirror
- 5 orthogonal polarization filters on operator's spectacles

Figure B.1 — Viewing device for stereo TV (in principle) — Method with polarized light

**Key**

- 1 linear polarizers
- 2 PLZT cell
- 3 PLZT glasses (shutter)
- 4 display controller
- 5 monitor

Figure B.2 — Viewing device for stereo TV (in principle) — Method with shutter

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