AN INDUSTRIAL ROBOT WITH A DRIVE UNIT COMPRISING A LIGHTWEIGHT ELECTRIC MOTOR AND A LIGHTWEIGHT SPEED REDUCER

The invention provides an industrial robot comprising a first robot part (38a) and a second robot part (4a) arranged to be moved in relation to each other, and at least one drive unit (1) arranged to move one of the robot parts (4a) during operation of the robot. The at least one drive unit (1) is arranged as a compact module (39) with a common housing (38) comprising a lightweight electric motor (40) and a lightweight speed reducer (5), the drive unit module (39) comprises a mounting flange (4), and the drive unit module is arranged such that the common housing (38) is connected to the first robot part (38a) and the mounting flange is connected to the second robot part (4a).
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TECHNICAL FIELD
The present invention relates to an industrial robot comprising at least one drive unit with an electrical motor.

BACKGROUND OF THE INVENTION
Robots of today are quite heavy in relation to the weight of the loads they are built to carry. The most critical part of an articulated robot with respect to its weight is the weight of the wrist and the upper arm, which means the weight of joints 3 - 6 (corresponding to axes 3-6 in Figure 5). Beside the weight of motors and speed reducers, weights of transmissions, bearings and structures for mounting of these components add up to inefficient weight to load relations. Usually, motors and speed reducers for the wrist joints are mounted at the rear part of the upper robot arm, which makes it necessary to use mechanical transmissions between the rear part and the front part of the upper arm. Moreover, gear assemblies are anyhow needed in the wrist and to support the transmission gear assemblies, several bearings and complicated arm structures are needed all over the upper arm.

In many applications low speed drive units are needed to rotate objects. Then it is often a big advantage to reduce the weight of the drive unit, especially when the drive unit is moved by other parts of the system it works in. Examples of such systems are vehicles, linear guide ways and robots. In the case of industrial robots, the most important issue with respect to weight is to reduce the weight of the wrist, which in turn makes it possible to reduce the power of the main axes and the weight of the moving parts of the robot. Such weight reductions imply lower robot cost, higher safety, easier installation, easier programming and improved performance.

In prior art robots, the design results in heavy robots comprising complicated arm structures. The prior art robot design makes assembly and maintenance difficult and expensive.
Consequently, there is a need for an industrial robot having a simple/uncomplicated design.

SUMMARY OF THE INVENTION
The object of the invention is to design a lightweight industrial robot. Another object is to design a modular and compact manipulator. Another object is to design a manipulator easy to assemble and maintain. Still another object is to design a stiff robot.

According to an aspect of the present invention, there is provided an industrial robot comprising the characterizing features of claim 1

Preferred embodiments are described in the dependent claims.

The solution according to the first aspect of the invention is to provide an industrial robot comprising a first robot part and a second robot part arranged to be moved in relation to each other. At least one drive unit is arranged to move one of the robot parts during operation of the robot. The at least one drive unit is arranged as a compact module with a common housing comprising a lightweight electric motor and a lightweight speed reducer. The drive unit module comprises a mounting flange, and the drive unit module is arranged such that the common housing is connected to the first robot part and the mounting flange is connected to the second robot part.

The present robot design comprises highly integrated lightweight drive units, which eliminates the need of the torque transmissions in an upper robot arm. Further, the design increases the efficiency of each joint drive. The drive unit is designed such that it is easy to mechanically adjust the components for optimal performance and that the assembly can be easily made, preferably automatically to minimize the robot cost.

In one embodiment, a lightweight electric motor comprises a stator and a rotor. A speed reducer comprises a wave generator and a flex spline. The motor is arranged integrated with the speed reducer.

In one embodiment the wave generator is integrated with the rotor.
In one embodiment each of the stator, the rotor, the wave generator and the flex spline is designed with a centre opening and is arranged integrated in the common housing such that a tubular passage is provided for through the common housing.

The hollow shaft design of the drive units is used for integrating process cables and hoses. Further it is used for compact stiff mounting of the drive units.

In one embodiment, at least one sensor means is arranged for control of the drive unit.

In one embodiment, the at least one sensor means is arranged for feed back control of the speed reducer.

In one embodiment, the at least one breaking means is integrated with the rotor.

The present drive unit design combines a lightweight motor with a lightweight speed reducer. These components are tightly integrated together with sensors needed for the control of the drive unit. This integration is made such that rotating shafts, bearings and housing are minimized by having the motor and speed reducer as close as possible to each other. This design makes the material and the bearings optimally used and results in a compact design.

It is also important to make use of a high speed motor together with a speed reducer with high gear ratio. In order to avoid overheating the motor should have a very low power loss and the gear should be lubricated in a separate chamber with oil or grease.

Using such drive units it is possible to design lightweight, compact, slender, modular and low cost robots for many applications. The lightweight property is important for safety and for applications where the robot is carried by tracks, gantry manipulators or vehicles. One important application in this respect is the portable robot to be used at smaller manufacturer sites where the robot must be moved around to different applications in order to obtain enough robot production time. The compactness and slenderness is important in space limited applications as for example in the final assembly of cars and other vehicles. Modularity is important in order to have low maintenance costs and for making it possible to custom design robots for different applications and still having a low manufacturing cost. Low cost is of course always important and to obtain this it is important with automatic assembly of robot
modules and lightweight design for low drive system cost. The lightweight robot can be used
for almost all the applications that robots are used for today and will even broaden the usage
of robotics. The robot will be a versatile tool for a lot of applications where manual work is
the only economical solution today.

In one embodiment, the at least one sensor means is a torque sensor. In this way a very
compact drive unit with built in output torque measurements is achieved, which makes it
possible to control the output torque of the drive unit and in that way compensate for the lack
of stiffness in the speed reducer.

In one embodiment, the torque sensor comprises a sensor shaft arranged within the tubular
passage of the drive unit. This gives the possibility to integrate a rotating wireless torque
sensor (for example the ABB torductor) with the joints for stiffness control.

In one embodiment, the robot is a six axes robot arranged to comprise six drive units. In one
embodiment, the robot is arranged to comprise a wrist with two drive units. In one
embodiment, the wrist is arranged to comprise three drive units. This integration of a compact
drive unit in a wrist provides for a design of a lightweight robot. With the drive unit module,
it is possible to design a very compact and efficient wrist.

Further, a compact drive unit can be integrated into the robot structure to obtain the main joint
2 or 3 (see Figure 14). The use of at least one lightweight highly integrated compact drive unit
opens up for using lightweight standard carbon tubes for the robot arms and to use assembly
technology used in aerospace industry as gluing combined with mechanical fixtures for
fastening carbon to the metal components needed in the joints.

In one embodiment, the robot is arranged to comprise at least one cable/hose, which is
arranged to pass through the tubular passage of at least two of the drive units.

In one embodiment, the robot is arranged to comprise at least one cable/hose arranged to pass
outside the tubular passage of at least one drive unit. This design is preferably used in
applications where it is more important to have a very compact wrist than having an
integrated process cable. One example of such an application is the assembly of small
components in confined spaces as in the interior of automobiles, refrigerators and washing
machines, where only a small gripper with minimum cabling or even wireless communication can be used.

In one embodiment, the robot is arranged to comprise at least one robot arm comprising at least one carbon fibre reinforced tube. By using as much carbon reinforced epoxy tubes as possible and by using aluminium for the mechanical support structures for bearings and drive units, a very lightweight robot with high performance can be built. The lightweight drive unit design described earlier is necessary to use for the wrist in order to obtain a breakthrough for lightweight robot design. However, the same drive unit design can also be used for the drive units of the main joints to further reduce the mass and inertia of the robot and to make the robot as modularized and easy to assemble and maintain as possible.

The feature "cables and hoses" are defined as at least one cable and/or at least one hose supplying any energy or medium or transmitting measurement and control signals within and through the drive unit. The provided tubular passage is provided to accommodate the cables and/or hoses arranged within the drive unit and passing through the inside of the drive unit.

Even though many different possibilities exist to make an efficiently integrated drive unit, the drive unit in Figure 3 will be used in the following description on how this type of drive units can be integrated in a robot to obtain efficient, lightweight, low cost and compact robot concepts.

BRIEF DESCRIPTION OF THE DRAWING
The invention will be explained more closely by the description of different embodiments thereof and with reference to the appended drawing in which:
Figure 1 is a drive unit according to an embodiment of the invention,
Figure 2 is the drive unit in Figure 1 in more detail,
Figure 3 is a cross section of the drive unit in Figure 1,
Figure 4 is a two axes drive unit according to an embodiment of the invention.
Figure 5 is a robot wrist comprising three drive units according to one embodiment of the invention,
Figure 6 is a robot wrist comprising three drive units according to one embodiment of the invention,
Figure 7a is a robot wrist comprising two drive units according to one embodiment of the invention,
Figure 7b is a robot wrist comprising three drive units according to one embodiment of the invention,
Figure 8a is a robot arm according to one embodiment of the invention,
Figure 8b is a robot arm according to one embodiment of the invention,
Figure 9 is a robot arm according to one embodiment of the invention,
Figure 10 is a torque sensor,
Figure 11 is a drive unit according to an embodiment of the invention comprising a torque sensor,
Figure 12 is a robot wrist comprising three drive units according to one embodiment of the invention,
Figure 13 is an industrial robot comprising six drive units according to an embodiment of the invention,
Figure 14 is the robot in Figure 13,
Figure 15 is an industrial robot comprising six drive units according to an embodiment of the invention,
Figure 16 is a drive unit according to an embodiment of the invention comprising a torque sensor.

In the following examples of lightweight highly integrated drive units are first given, then it is shown how these drive units can be used for the design of lightweight compact modular wrists and after that the design of a whole robot is shown.

**Figure 1** is a lightweight drive unit 1 designed as a drive unit module 39 with a common housing 38 comprising a high speed motor compartment 2 and a low speed gear compartment 3. The motor compartment 2 comprises a lightweight rotor 6, a lightweight stator 7 and a first sensor means 8a. The gear compartment 3 comprises a lightweight speed reducer 5. The rotor and the stator are axially mounted from a direction A. The speed reducer with a wave generator and a flex spline are mounted from the same axially direction A.

Further, the drive unit comprises an outgoing mounting flange 4 and a second sensor means 8b. The drive unit is an integration of a lightweight electric motor 40, a lightweight speed...
reducer and lightweight sensors 8. The drive unit also comprises a brake means with a brake disc and a brake shoe, which is presented in more detail in Figure 2.

The Figure 1 is an integration of a lightweight motor, a lightweight speed reducer and lightweight sensors to obtain a lightweight wrist. The lightweight motor for this application is designed to have a high magnetic field density motor with very strong magnetic field in the air gap and to be able to obtain very high motor speed without unwanted heating. One way to obtain these features is to have an ironless thin laminated stator winding 7 and a rotor 6 with magnets generating a strong field in a thin air gap across the stator winding. This arrangement is made by having a cylindrical stator laminate and a cylindrical rotor with a cylindrical slit, into which the stator cylinder is mounted.

The drive unit 1 is designed as a drive unit module 39 to be used in an industrial robot comprising a first robot part 38a and a second robot part 4a arranged to be moved in relation to each other. The drive unit 1 arranged to move one of the robot parts during operation of the robot. The compact drive unit module 39 comprises a common housing 38 comprising a lightweight electric motor 40 and a lightweight speed reducer 5. The drive unit module 39 comprises a mounting flange 4, and the drive unit module is arranged such that the common housing 38 is connected to the first robot part 38a and the mounting flange 4 is connected to the second robot part 4a. The first robot part comprises a robot arm or a connection plate. The second robot part comprises a robot arm, a connection plate or a drive unit housing. This will be further described in the following.

Figure 2 is a drive unit comprising a thin laminated stator winding 11 mounted on a wall 34 between the high speed (motor) 2 and low speed (gear) compartment 3. A rotor 10 is positioned with high accuracy on the outer shaft 12 to make it possible to rotate the rotor without touching the stator 11 in the thin air gap of the rotor. The rotor shaft 12 is connected to the housing 2 by means of two bearings 13 and 14, which could be ball- or needle bearings to obtain a lightweight wrist.

The drive unit comprises an encoder concept 9 comprising a rotating encoder ring 18 for measuring the angle of rotation of the rotor and is mounted via a mechanical connection 17 on the rotor 10. The encoder concept further comprises a fixed encoder ring 19, which is equipped with wiring connections and which is mounted on the wall 34 between the high
speed 2 and low speed 3 compartments. The encoder rings 18, 19 are simply glued to the mechanical connection 17 and the wall 34. Connected to the rotor is also a cylindrical brake disc 15 which can be engaged by a cylindrical brake shoe 16 mounted on the housing wall 35.

The shaft 12, rotating with high speed, is mechanically connected to a wave generator 20. When the wave generator is mounted on the shaft 12, it is important to be able to adjust the wave generator in radial direction such that the vibrations of the gear are minimized. This can be made by rotating the motor when the speed reducer is assembled and the wave generator is free floating in radial direction in relation to the high speed shaft. With such a mounting action the wave generator will automatically find the assembly position for minimum vibrations. The wave generator 20 is then fixed to the high speed shaft 12 by means of screws 20c via a disc 20b fixed to the shaft 12. In order to be able to adjust the wave generator after the mounting of the motor and speed reducer, there are holes 22b, 33b in the flex spline gable 22a and in the speed reducer housing 33 respectively. The wave generator 20 is fastened using a tool 37 operating through 33b, 22b for mounting a screw 20c in a hole of the wave generator. If a flange is mounted on the drive unit before fastening the wave generator, the flange is arranged with at least one hole too.

Via a bearing 21 the wave generator engages gear teeth between the flex spline 22 and the gear ring 23. In this way very high gear ratios can be obtained between the wave generator and the flex spline. The flex spline is mounted on an inner shaft 25, which is connected to the housing by means of two bearings 24 mounted on a ring 36 on the housing 35 and 26 mounted on the housing 33. A tubular passage 31 formed by the inner shaft 25 can be used for cables 95. In one end of the inner shaft 25 a flange 29 is mounted with holes 30 for the mounting drive units, tools or other objects that are rotated by the drive unit. A low speed encoder 27, 28 is mounted between the back side of the flange 29 and the gable wall 33a of the low speed housing 33 with the encoder ring 27 having the electrical connections on the gable wall and the other encoder ring 28 on the flange. As for the high speed encoder rings 18, 19 also these encoder rings can simply be mounted by gluing. To prevent dirt and fluid from entering between the encoder rings a sealing should be used between the flange and the gable wall. There is also a need of sealing between the oil-filled low speed compartment and the high speed compartment. One such sealing is symbolized by a ring 32 and if the bearing 14 between the compartments is not tight, a sealing is also needed in connection to this bearing.
It is noted that each embodiment described comprises at least one hole in a gable of the flex spline. This is not shown in all Figures since they are more schematic.

Instead of having a cylindrical stator and rotor, these components can also be manufactured as discs, which will give a flat motor design. The motor components are mounted in the motor compartment 2 of the drive unit module 1.

As a lightweight speed reducer a Harmonic Drive technology is adopted. The main components of a Harmonic Drive gear assembly 5 are the wave generator on the high speed side and the flex spline on the low speed side. These components are integrated into the gear compartment 3, which is filled with oil or which contains grease for the lubrication of the gear teeth of the flex spline and of the gear ring outside the flex spline. The Harmonic Drive technology provides outstanding torque to weight ratios.

Since this type of lightweight speed reducer has a built in flexibility, an encoder can be used to increase the stiffness of the drive unit by means of feedback control. The encoder selected is a capacitive encoder 8, which is accurate, light weight, easy to integrate mechanically, robust and of low cost.

An alternative encoder concept 9 comprises groups of 4 transmitting electrodes for each receiving electrode for measuring the rotation angle with very high precision.

Since rotation angle is also needed to be measured on the high speed side because of the requirements from the servo control (including motor commutation), capacitive encoders can be mounted both in the motor compartment 2 and optionally on the outgoing mounting flange 4. The capacitive encoder technology is critical to obtain measurements on the low speed side since no other technology has the needed combination of high precision, robustness, easy to integrate, low weight and low cost. The high speed encoder on the motor side can, however, be replaced by for example a resolver type of angle measurement sensor, even if this will be heavier, take a bigger space and be more difficult to integrate into the motor compartment 2.

**Figure 3** is an elaborated design of a drive unit using two compartments as in figure 2. A rotor 140 is mounted on the high speed shaft 143 using a conical bushing ring 142, which is
pressed between the rotor part 140 and the shaft 143 using a nut 145, which is screwed on the
shaft 143. Between the nut and the bushing is a washer 144. In this way, it is very easy to
mount the rotor with high precision on the high speed shaft. The high speed shaft 143 is
mounted on the housing gable wall 146 via a ball bearing 147 and on the middle section wall
via a needle bearing 150. The bearing type in the gable wall 146 is selected to allow accurate
adjustment (with for example a ball track bearing) of the shaft 143 without obtaining stress in
the shaft or the bearings supporting it. The gable wall bearing 147 is pre stressed between a
clip ring 148 and the gable wall 146. In order to avoid the need of lubricating the gable wall
bearing this can be a ceramic bearing. The rotor consists of a magnet carrying structure and
the magnets 141. It is also equipped with a wall 103, which carries a brake disc, engaged by a
magnetic brake 104b using a brake pad 104a. A capacitive encoder ring 155 is mounted on the
rotor and the other ring 156 of the high speed encoder is mounted on the gable wall 146. In
the air gap of the rotor the stator 158 is mounted. The windings from the fixed encoder ring
156 and the stator 158 are situated in the free space outside the rotor part 140 and will get out
through a hole (not shown) in the high speed compartment wall.

The wave generator 164 of a Harmonic Drive speed reducer is mounted on the high speed
shaft 143 with screws 162. The diameter of the screw holes in the wave generator are made
somewhat larger than the diameter of the screws making it possible to adjust the wave
generator for minimum speed reducer vibrations. The gear ring 163 of the Harmonic Drive is
mounted using screws 162 early in the assembly sequence. These screws are also used to
mount the cylindrical high speed compartment part 159 on the cylindrical low speed
compartment part 161. In order to obtain as low weight as possible and in order to match the
temperature coefficient of the steel parts of the speed reducer, the low speed compartment part
could be manufactured in special Aluminium alloys. The flex spline unit 166 is mounted on
the flange 170 and on a bearing 171, preferably of cross track type, by means of screws 169
running into a ring 167 with screw-thread holes. The screws 169 clamp the flex spline 166
between the ring 167 and another ring 168, which in turn is used to clamp the bearing 171
against the flange 170. After trimming the adjustment of the wave generator 164 on the high
speed shaft 143 by turning the rotor shaft around, the wave generator screws 165 are tightened
by a screw driver using holes in the flange 170 and the flex spline 166. If not all the flex
spline screws 169 are used during the adjustment process, the holes for the lacking screws can
be used to reach the wave generator screws 165.
The bearing 171 is clamped between the high speed compartment wall 161 and a ring 172 using screws 184. The low speed encoder rings 176, 177 are mounted on the assembly ring 172 and on the back side of the face plate 182 respectively. A tube 157 inside the high speed shaft is introduced to make a sealing of the low speed compartment possible. Thus, the sealing rings 181 and 160 prevent oil from leaking into the centre of the drive unit. Moreover, a sealing ring 149 is used to prevent oil leakage into the motor side and another sealing ring 183 is used to avoid leakage to the low speed encoder.

The conic mounting of the rotor 140 is made directly on the rotor cylinder and the brake 151 — 153 is of a cylindrical type and the stator is mounted on the outer housing wall 159. Thus, only the encoder rings 155 and 156 occupy the gable wall side and can therefore be made broader to include extra electrodes for absolute angle measurements. The cable protection tube 157 is fixed to the housing at the high speed compartment gable and mounted on a bearing 180 in the flange part 170.

At least one of the rotating sealings, preventing speed reducer lubrication from entering the motor compartment 110 and 149, is a labyrinth sealing or an elastomeric sealing with ultra low friction.

In one alternative embodiment, the rotor is mounted in the opposite direction, meaning that the stator 158 will be mounted on the gable wall and the encoder rings between the rotor and the middle wall of the drive unit. However, then the assembly will be more difficult. In order to be able to use broader encoders 177, 178 also on the low speed side the flange 170 diameter has to be been increased and a protection ring with a sealing 174 has to be introduced (not shown).

The compactness of the drive unit can be further increased by integrating the wave generator with the rotor as illustrated in Figure 4. Here the sealing between the gear part and the motor part gets more complex. Thus, a sealing ring 85 is used between the rotor 68 of the motor and the flex spline 81. It is also necessary that the rotor bearing 69 and shaft bearing 84 are sealed. The fixturing of the wave generator 78, 79 is made through holes in the flex spline 81 and the gable wall on the flange 89 side of the housing. A disc brake ring 74 is mounted on the rotor bearing 69 using a support ring 77 and on the same support ring an encoder support ring 76 is mounted. Capacitive encoder rings 72, 73 on the high speed side and the low speed side 86,
87 are used. From assembly point of view it is very important that all the assembly is made axially from one direction. This is made possible thanks to the radial symmetry of the integrated drive unit.

**Figure 5** is a robot wrist design comprising lightweight compact drive units. It outlines the potential of using three of the drive units described Ia, Ib and Ic, as a wrist assembly on the fore arm of an industrial robot. As a comparison a typical high performance robot used in industry today is shown (the ABB IRB2400 with a maximum load capacity of 10 kg). When the fore arm tube 96 connecting the wrist assembly Ia, Ib and Ic with the main axes of the robot is made from carbon reinforced epoxy it is possible to reduce the total weight of the forearm of a robot of the ABB IRB2400 type with 5 - 10 times. This will drastically reduce the torque and power need of the main axes and the main axes mechanical structure can simultaneously be designed for a much lower weight, giving a cheaper, safer and lighter robot, which is easier to control. In the figure the drive units are connected by simple plates 93 and 94. The hollow centres of the drive units are used for the process cables 95.

**Figure 6** is an alternative mounting of the drive units Ia, Ib and Ic with respect to the process cables 95. Here the shafts of unit Ia and Ic are in a common plane at right angle to the shaft of unit Ib. Unit Ib is mounted on unit Ia with the plate 98 and unit Ic is mounted on unit Ib with the simple structure 99. The process cable 95 is arranged passing through a carbon tube 96.

If it is not necessary to integrate the process cabling 95 in the upper arm it is possible to build an even more compact modular wrist than in Figure 6.

**Figure 7** comprises Figure 7a and 7b, where Figure 7a is a two axes wrist. Figure 7b is a three axes wrist, which can easily be obtained by just adding one drive unit module 293 to the two axes wrist according to Figure 7a. If it is not necessary to integrate the process cabling in the upper arm it is possible to build an even more compact modular wrist than in Figure 5.

**Figure 7a** is a two axes wrist comprising a first drive unit 283 for the first wrist joint is mounted with its mounting flange on an end plate 281. The end plate is fixed to the carbon fibre tube 280, which constitutes part of an upper arm of a robot. On the outside of the drive unit 283, two gable plates 284, 285 are mounted. These plates will be rotated relative the
upper arm 280 when the drive unit 283 works. The gable plates 284, 285 hold a shaft 286, on which a second wrist joint drive unit 289 is mounted. Actually, the flange 287 is not needed in the figure 6a. In another alternative, the shaft 286 is replaced with one mounting flange in each end of the drive unit 287 (not shown).

As an alternative (not shown) the wrist can be designed without the gable plate 285, whereby the mounting flange 287 of drive unit 289 is mounted on the gable plate 284. The bearing 288 in drive unit 289 will get a lower load when the drive unit is mounted on the shaft 286 as in the Figure 6a, which means a higher stiffness in relation to the wrist weight.

What solution to use depends on the layout of the modular design and on the application requirement. For example, one mounting flange at each end of the drive unit will increase its length, making the wrist broader but will make the module more versatile. The mounting flange 290 of the wrist is then mounted directly on the housing of the second wrist joint drive unit.

**Figure 7b** shows the easiness given by the modular design to add a joint to the wrist. Here a third wrist joint is obtained simply by mounting the drive unit 292 on the housing of drive unit 289 using an attachment plate 291. The wrist tool mounting flange will now be the mounting flange 293 of drive unit 292.

In order to handle process cables and hoses that are stiff and cannot take to much bending or twisting, an open upper arm design according to Figure 8 can be implemented using the hollow shaft design of the lightweight drive units. **Figure 8a** shows the upper robot arm seen from above. A first wrist joint drive unit 295 is located a distance from a second wrist joint drive unit 298, separated by a beam 297 giving a free space for the process cable/hose 304. Drive unit 295 is mounted in the upper arm fixed part 294, which can be an aluminium tube. One end of the beam 297 is mounted on the output mounting flange of drive unit 295 via the part 296. In the other end of the beam 297, the output mounting flange of drive unit 298 is mounted, giving a second wrist joint at right angle to the first wrist joint. On the housing of drive unit 298 the housing of the drive unit 303 is mounted by means of the structure 301. The handling of the process cable/hose is shown in Figure 8b.
In Figure 8b, the cable 304 goes through the hollow shaft of drive unit 295, is bent over drive unit 298 (with the unused hollow shaft 300) and goes through the drive unit 303. In this way the process cable/hose is free to bend with a large radius and twist over a long distance making the use of stiff cables possible without degrading the cable lifetime and inflicting high cable forces on the drive units. The drive unit 295 must be designed to take big bending torques on its output flange, which means larger bearings and higher upper arm weight.

Figure 9 is an alternative embodiment comprising a first wrist joint drive unit 305 is arranged close to a second wrist joint drive units. In order to still handle the cable/hose the first wrist joint drive unit 305 is mounted at an angle in such a way, that the cable/hose 304 can go/pass through the hollow shaft without extra bending.

The output flange of a drive unit 305 is mounted on a shelf 306, in turn mounted at right angle on an arm beam 297. The output flange of drive unit 308 of the second wrist joint is mounted on the housing of drive unit 305 via the connection 307. Drive unit 310 for the third wrist joint is mounted with the connection 309 on the housing of drive unit 308 as in Figure 7. In order to optimize the movements of the cable/hose 304, guiding wheels 311 - 314 are used. The guiding wheel 312 is a lightweight bearing around the housing of drive unit 308. This bearing is placed on the middle of the cylindrical drive unit 308 housing in such a way that there is space for mounting of the connector 309. The guiding wheel 311 is mounted on a swing able arm, with springs or centring mechanism in such a way that it will always be in the middle between drive units 305 and 310.

One alternative is to mount the housing of drive unit 305 on the beam 297 and the output mounting flange on the connection 307 to drive unit 308 (not shown).

One way to increase the stiffness of a drive unit against torque disturbances is to measure the outgoing torque and feedback the torque signal to the robot controller. Figure 10 is a torque sensor, which measures the torque transmitted by a sensor shaft 318. This shaft is in the sensor zone 317 covered by a pattern with material having a well defined magnetostrictive effect. Around the sensor zone 317, there is a yoke and by means of a winding the torque is measured by measuring changes in the winding impedance. One big advantage with this magnetostrictive sensor principle is that no windings need to be connected to the rotating shaft 318.
Figure 11 shows how such a magnetostrictive sensor shaft can be integrated with the drive unit in Figure 3. The output flange of the drive unit 315 is connected to the disc 316, on which one end of the shaft 318 is centrically mounted. The shaft with the sensor zone 317 is in its other end mounted on the disc 319, which is now the mounting flange of the drive unit. In order to obtain high stiffness of the flange 319, this is connected with a bearing 320 to the drive unit housing. In this way a very compact drive unit with built in output torque measurements is achieved, which makes it possible to control the output torque of the drive unit and in that way compensate for the lack of stiffness in the speed reducer.

Figure 12 is a wrist designed comprising the drive unit type according to Figure 11. The output flange 323 of the first wrist joint drive unit is mounted on the end part 322 of the arm tube 321. The housing of the first wrist joint drive unit is mechanically connected to the housing of the second wrist joint drive unit by 324. Instead of a one sided mounted bracket 324 as in the Figure 12, a cylinder could be used to obtain a robot wrist with the same shape as the arm tube 321.

An alternative is that the output flange of the first wrist joint is mounted on the housing of the second wrist joint drive unit and that the housing of the first wrist joint drive unit is mounted on the arm end part 322. The output flange of the second wrist joint 325 is via 326 connected to the housing of the third wrist joint and the output flange of the third wrist joint 327 is used for mounting of the tool (not shown). In this way a compact wrist with increased stiffness using torque control can be obtained.

At least one lightweight drive unit makes it possible to design a lightweight robot. Figure 13 is a robot designed with a plurality of lightweight compact drive units.

The lightweight drive unit design 210 is used for the implementation of three wrist drive modules 211, 212 and 213, forming the joints 6, 5 and 4 of the robot (see Figure 14). The three drive modules 211, 212 and 213 are connected by the mechanical structures 215 and 216 in such a way, that process cables and hoses 214 can easily be integrated with the wrist (see Figure 5). The joint 4 drive unit 213 is mounted inside one end of an upper arm tube 217, which is preferably made of carbon reinforced epoxy in order to obtain a high stiffness to weight ratio.
The upper arm tube is in its other end mounted on the holder 220 of a lower arm 229 and a holder 225 of a parallel beam 228. The holder of the lower arm 220 consists of a fork formed structure supporting one bearing 221 on each side of the cylinder 219 fixed to the upper arm 217. This cylinder is, in one alternative, made of metal. It is preferably glued on the outside surface of the carbon tube of the upper arm 217 and works as a support structure for the bearing arrangement 221. The fork formed structure 220 is in turn mounted on the carbon tube 229 of the lower arm by gluing a cylinder 222 on the lower arm tube 229. In a similar way the fork 225 for the parallel beam 228 is glued on the parallel beam end using a cylinder 227. The bearing holder 224 for the parallel beam 228 is mounted on the upper arm 217 by means of gluing a cylinder 223 on the carbon tube of the upper arm 217. The bearing holder 224 for the parallel beam is hollow making it possible to have the cabling and hoses going through the upper arm and then through the hollow centres of the drive units of the wrist.

The lower ends of the carbon tubes of the lower arm and the parallel beam are glued to cylinders 235 and 230. These cylinders are then mounted on to the joint 2 drive unit 236 behind the gable of the fork 237 and fork 231 of the parallel beam arm 233. The parallel beam arm 233 is driven by the joint 3 drive unit 234 and is connected to the parallel beam by means of bearings 232 on its fork 231. The bearing arrangements for the upper arm 219 - 222, the parallel beam 223 - 227 and 230 - 233 have similar design and can be standardized for a robot family, making modularisation efficient. Finally, joint 1 consists of a bearing between the robot foot 239 and the rotating base platform 238. Joint 1 is driven by a drive module 240 on the base platform.

By using as much standard carbon reinforced epoxy tubes as is possible and by using aluminium for the mechanical support structures for bearings and drive units, a very lightweight robot with high performance can be built. The lightweight drive unit design described earlier is necessary to use for the wrist in order to obtain a break through for lightweight robot design. However, the same drive unit design can also be used for the drive units 234, 236 and 240 of the main joints to further reduce the mass and inertia of the robot and to make the robot as modularized and easy to assemble and maintain as possible.

**Figure 15** is an industrial robot comprising a joint 3 designed to allow backward bending of an upper arm. A shaft 330 is mounted inside the hollow shaft of the drive unit 334. The shaft 330 is fixed to the gables 328 and 329, which are mounted on the lower arm 335. The housing
of the drive unit 334 is mounted on the support structure 331, on which the cylinder 332 is mounted. This cylinder is used for the mounting of the upper arm tube 333, preferably by gluing. The same arrangement as for joint 3 can be made for joint 2. A shaft is mounted on the gables 336 and 337. The housing of the linear module is mounted on the structure 340, on which the lower arm tube 335 supporting cylinder 339 is mounted. This design results in a very compact robot and slender robot.

In order to obtain a robot with increased stiffness, the drive unit with an integrated torque sensor according to Figure 11 can be used. Then, the joints 2 and 3 of the robot in Figure 15 can be designed according to Figure 16. Figure 16 is the design of joint 2 and a corresponding design can be made for joint 3. Thus, the output flange 343 of the drive unit 342 is mounted on the gable 336 and the other gable 337 is connected to the sensor shaft mounting disc 344 by means of the bearing 341. The gables are mounted on the base 338 and the arm tube 335 is mounted on the housing of the drive unit via the cylindrical tube holder 339.

The components in Figure 3 are:
140: Rotor
141: Rotor magnets
142: Conical bushing ring for high precision mounting of the rotor on its shaft (143)
143: High speed motor shaft
144: Washer
145: Nut for fixing the conical bushing (142)
146: Gable wall for the high speed compartment
147: Bearing for the high speed shaft (143)
148: Circular clip for the mounting of the bearing (147).
149: Sealing to avoid oil leakage from the low speed to the high speed compartment.
150: Needle bearing for the high speed motor shaft (143)
151: Cylindrical braking drum mounted on the rotor (140)
152: Braking pad
153: Magnetic braking mechanism
154: Steel ring for the rotating encoder ring (155)
155: Rotating encoder ring (having no wiring)
156: Fixed encoder ring (with the wiring)
157: Protection tube mounted on the gable (146)
158: The stator
159: High speed compartment housing
160: Sealing for oil or grease
161: Low speed compartment housing
162: Screws for mounting of Harmonic Drive gear ring and for mounting the high speed compartment on the low speed compartment
163: The gear ring of the Harmonic Drive speed reducer
164: The wave generator of the Harmonic Drive speed reducer
165: Screws to mount the wave generator on the high speed motor shaft (143). The hole in the wave generator must have a diameter bigger than the screw to make adjustment possible.
166: The flex spline of the Harmonic Drive speed reducer
167: Ring with screw threaded holes for fastening the flex spline to the flange (170)
168: Ring for the mounting of the flange bearing (171) and the flange sealing (181)
169: Screws for mounting the flex spline (166), the flange bearing (171), the flange sealing (180) and the flange (170)
170: The flange structure
171: The flange bearing (preferably of cross roller type)
172: Ring for mounting of the flange bearing (171) on the low speed compartment housing wall (161)
173: Screw to mount the flange bearing fastening ring (172)
174: Sealing to avoid dust and fluid entering the encoder rings (177, 178)
175: Protection ring for the encoder rings (177, 178)
176: Metal ring for the mounting of the fixed encoder ring (177)
177: Fixed encoder ring with wiring
178: Rotating encoder ring mounted on the flange structure (170)
179: Mounting screw holes on the face plate of the flange structure (170)
180: Bearing for the protection tube (157)
181: Sealing for oil or grease leakage
182: Protection for the encoder rings
183: Sealing for oil or grease leakage
184: Screw for mounting the metal ring 176 used for mounting the fixed encoder ring 177
CLAIMS

1. An industrial robot comprising a first robot part (38a) and a second robot part (4a) arranged to be moved in relation to each other, and at least one drive unit (1) arranged to move one of the robot parts (.) during operation of the robot, characterized in that the at least one drive unit (1) is arranged as a compact module (39) with a common housing (38) comprising a lightweight electric motor (40) and a lightweight speed reducer (5), the drive unit module (39) comprises a mounting flange (4), and the drive unit module is arranged such that the common housing (38,) is connected to the first robot part (38a) and the mounting flange is connected to the second robot part (4a).

2. An industrial robot according to claim 1, wherein the lightweight electric motor (40) comprises a stator (7, 11) and a rotor (6, 10).

3. An industrial robot according to claim 2, wherein the speed reducer (5,) comprises a wave generator (20) and a flex spline (22).

4. An industrial robot according to claim 3, wherein the electric motor (40) is arranged integrated with the speed reducer (5).

5. An industrial robot according to any of the preceding claims, wherein the wave generator (20, 78,79) is integrated with the rotor (6, 10, 68).

6. An industrial robot according to claim 4, wherein each of the stator (7, 11), the rotor (6, 10), the wave generator (20) and the flex spline (22) is designed with an centre opening and is arranged integrated in the common housing (38) such that a tubular passage (31) is provided for through the common housing.

7. An industrial robot according to claim 5, wherein at least one sensor means (8) is arranged for control of the drive unit (1; 315).
8. An industrial robot according to claim 7, wherein the at least one sensor means is an encoder (72, 73).

9. An industrial robot according to claim 5, wherein at least one sensor means (9) is arranged for feedback control of the speed reducer.

10. An industrial robot according to claim 9, wherein the at least one sensor means is an encoder or a resolver.

11. An industrial robot according to claim 2, wherein at least one breaking means (15) is integrated with the rotor (10).

12. An industrial robot according to claim 7, wherein the at least one sensor means (317) is a torque sensor.

13. An industrial robot according to claim 10, wherein the torque sensor comprises a sensor shaft (318) arranged within the tubular passage (31) of the drive unit.

14. An industrial robot according to any preceding claim, wherein the robot is a six axis robot arranged to comprise six drive units (240, 236, 234, 213, 212, 211).

15. An industrial robot according to claim 12, wherein the robot is arranged to comprise a wrist with at least two drive units (283, 289).

16. An industrial robot according to claim 13, wherein the wrist is arranged to comprise three drive units (Ia, Ib, Ic; 283, 298, 292).

17. An industrial robot according to any of claims 12-14, wherein at least one cable/hose (95) is arranged to pass through the tubular passage (31) of at least two of the drive units (la, lb, lc; la, lc; 295, 303; 305, 310).

18. An industrial robot according to any of claims 12-14, wherein at least one cable/hose (95, 304) is arranged to pass outside the tubular passage of at least one drive unit (lb; 283, 289; 283, 289, 292; 300, 308).
19. An industrial robot according to any preceding claim, wherein the robot comprises at least one robot arm comprising at least one carbon fibre reinforced tube (321; 217,228,229; 335,333).

20. An industrial robot according to any of the preceding claim, wherein the first robot part (38a) comprises a robot arm (96, 294, 333) or a connection plate (93, 94, 284, 285, 286, 301, 307, 309, 324, 326).

21. An industrial robot according to any of the preceding claim, wherein the second robot part (4a) comprises a robot arm (280, 297, 321), a connection plate (93, 94, 98, 99, 281, 284, 286, 291, 296, 297, 306, 309, 316, 322, 326, 327), or a robot tool.
Fig. 4
Fig. 16
INTERNATIONAL SEARCH REPORT

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B25J F16H

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

Electronic data base consulted during the international search (name of data base and where practical, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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