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On a New Generation of Torque Controlled Light-Weight Robots

G. Hirzinger, A. Albu-Schäffer, M. Hähnle, I. Schaefer, N. Sporer

DLR Oberpfaffenhofen
German Aerospace Center
Institute of Robotics and Mechatronics
D-82234 Weßling
Gerd.Hirzinger@dlr.de

Abstract

The paper describes the recent design and development efforts in DLR´s robotics lab towards the second generation of light-weight robots. The design of the light-weight mechanics, integrated sensors and electronics is outlined. The fully sensorized joint, with motor and link position sensors as well as joint torque sensors enables the implementation of effective vibration damping and advanced control strategies for compliant manipulation. The mechatronic approach incorporates a tight collaboration between mechanics, electronics and controller design as well. Thus we hope, that important steps towards a new generation of service and personal robots have been achieved.

Introduction

Experts believe that service robotics will become a driving force for the economy of industrial countries like the automobile industry nowadays.
A huge market seems to arise for smart light-weight robots. Purely position controlled standard industrial robots with a load to weight ratio of 1:10 or even less do not have the performance and features needed for future robotic applications (in particular on mobile platforms).
Robots with kinematics and sensory feedback capabilities similar to the human arm are urgently needed. DLR´s new light-weight robot incorporates a lot of advanced technologies for such a new generation of service robots. The most important features are high load to own weight ratio, joint torque control (allowing programmable impedance, stiffness and damping), increased flexibility and manipulability due to a 7 degree of freedom kinematics, low power consumption and fully integrated electronics and sensors.
The underlying mechatronics approach is described in this paper.

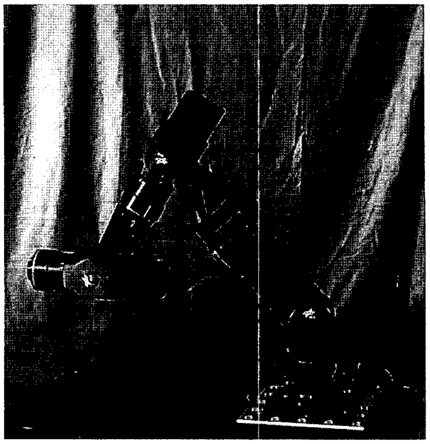

Fig. 1 DLR´s new light-weight robot II

1. Mechanics

For service robotics and mobile robots very light-weight arms with a good ratio of payload to weight are required. A robot arm mounted on a mobile platform should be able to dynamically move masses of 8kg. With a dexterous hand, such a manipulator is able to perform various handling tasks in human environments. A reasonable overall length of such an arm is about 1m.
Taking these requirements into account, we started a kinematic simulation to determine the best joint configuration. Based on the kinematics and desired payload, the required dynamic joint torques were calculated. Suitable motors and gears were chosen to obtain the desired joint torques.
The design of the mechanical parts and the integration of all electronic components was done by using modern 3D-CAD techniques. This resulted in a virtual prototype of the new light-weight robot which could be easily manufactured and assembled.

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1.1. Kinematic Simulation

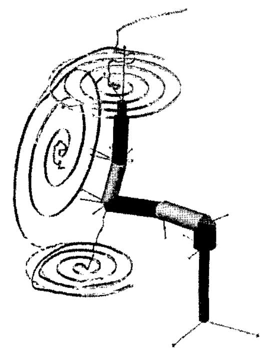

Fig. 2 kinematic simulation

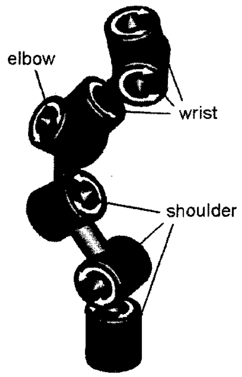

Fig. 3 robot kinematics

Based on the number of joints (7), the payload (8kg), the overall length (1m) and the tasks to be performed, the kinematic simulation should provide an optimal joint configuration. In our simulation we have chosen a trajectory consisting of three perpendicular spirals [Fig. 2]. As a result, it was suggested to equalize the distances between joint 2-4 and to use 3 perpendicular pitch joints for joint 2-4.

1.2. Joint Torque Requirements

Knowing the kinematics, it is important to evaluate the maximum dynamic torque of each joint in order to design suitable actuators:

Joint	1	2	3	4	5	6	7
Torque [Nm]	26	162	107	62	24	24	24

Table 1 joint torques

To evaluate the joint torques one needs at least the masses of all segments together with their centers of gravity. At the beginning of the design process these parameters are unknown and have to be appraised. For an initial estimation the parameters of our first light-weight robot were used [5],[7]. The design process was an iterative optimization. After having built up one joint, we were able to calculate the required joint torques for the whole robot [Table 1].

1.3. Design of the Light-Weight Structure

Meeting the guidelines of building a robot with a payload of 8kg and an overall weight of less than 17kg requires the design of an extremely light-weight structure. To compensate the joint elasticity, torque sensors are implemented in each joint. They allow various sophisticated control methods like vibration damping and stiffness control.

Furthermore, one has to use motors and gears with a very good output-torque to weight ratio. High performance brushless DC-motors from Kollmorgen and light-weight Harmonic Drive gears seemed both very suitable.

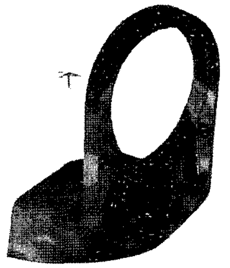

Fig. 4 FEM calculations

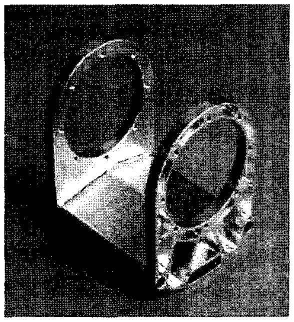

Fig. 5 manufactured part

Due to the light-weight aspect, most structural parts consist of aluminum, the link between joint 2 and 3 is made out of carbon fiber. The usage of extremely light-weight structures requires a close look at the highly loaded mechanical parts. It is necessary to maximize stiffness and strength of the structures while keeping in mind that weight must be reduced. This is done by using Finite Element Methods (FEM) [Fig. 4]. The main structure is non-modular with modular subassemblies. Despite of having a variety of different housings, this turned out to be a reasonable way to maximize the payload to weight ratio.

1.4. Virtual prototype

The light-weight robot is designed using a modern 3D CAD system. All mechanical parts as well as the electronic components are shaped in detail and have a density assigned to them forming a so-called virtual prototype.

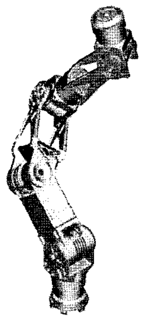

Fig. 6 mechanical structure

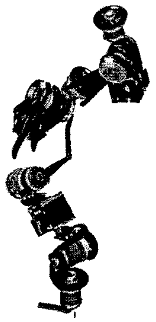

Fig. 7 electronics

Thus it is possible to retrieve masses, centers of gravity and mass matrices for single components as well as for the whole robot. The possibility of getting important model parameters from the model simplifies the identification of the arm significantly. The geometrical data of the electronic components have been obtained via the interface between the mechanical and electronic CAD tool.

The electronics was effectively integrated in the whole design. In addition, the internal structure of the virtual prototype allows an easy animation and visualization.

1.5. Multi-Sensory Joint Design

Each joint contains a torque sensor, a link position sensor and a motor position sensor. Furthermore, all joints are equipped with electromagnetic brakes. All these components, including motor and gear are placed inside the housing to be as space-saving as possible. We use motors without housing, special short and light-weight Harmonic Drive gears and modified electromagnetic brakes with reduced power consumption and decreased weight.

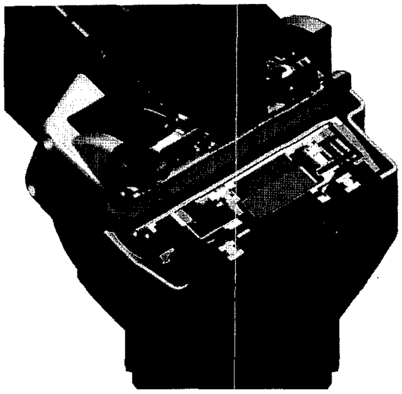

Fig. 8 Cross section of joint 2

The gears are provided with aluminum crafted wave generators and circular splines. All housings are made of aluminum (saving 40 % weight) and are designed to transfer thermal energy from the motor to the surrounding air. All joints are equipped with hollow shafts for the internal cabling.

2. Electronic components of the light-weight robot

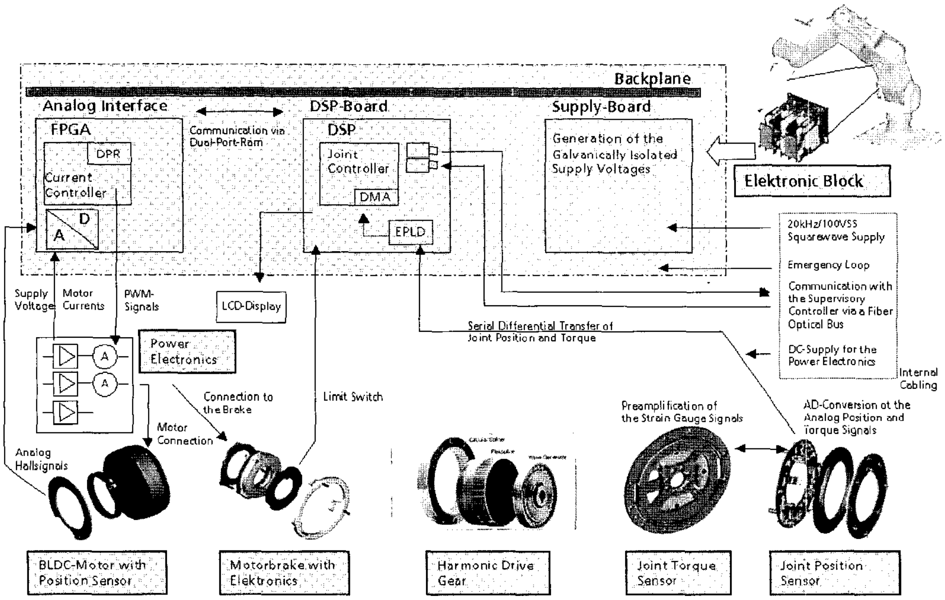

Fig. 9 components of the light-weight robot

For setup and maintenance reasons we have decided to use a backplane concept for the main electronic boards.

One backplane is designed for carrying electronics for two joints. Joint 7 and 6, Joint 5 and 4, Joint 3 and 2 share each one electronic block, which is integrated in the robot structure. The electronics for joint 1 is located in the base of the robot.

The electronic block is build up with a backplane, a supply board, two DSP boards and two analog interfaces. The electronics of the whole robots consumes less than 80W.

Since digital, analog as well as the power converter electronics has to be integrated close together it is inevitable that the required voltages have to be generated galvanically isolated. Commercially available isolated DC-DC converters are too bulky for integration. Their output voltages are not very accurate and the noise and ripple is too high for the analog measuring systems.

The light-weight robot has a two step conversion system. In the base of the arm a 20kHz, 100V peak to peak, squarewave voltage is generated. This AC-voltage can be transformed on the supply-boards via tiny ring core transformers. The voltages are rectified and fed into low dropout linear voltage regulators. The linear regulators guarantee an accurate and stable output voltage over the needed temperature and load range. For highest precision each individual joint can synchronize the AD-converters as well as the switching of the power electronics with the 20kHz signal. This supply concept has already been successfully used during the ROTEX mission. ROTEX was the first robotic system in space. [6]

Besides the galvanic isolation the grounding scheme has to be properly worked out to avoid ground loops and interference between the individual electronic components.

2.1. Supply-Board

The supply-board generates the galvanically isolated voltages for the digital, analog as well as the power converter electronics for two joints (2 x 5V digital, 2 x 5V analog, 2 x 5V and 2 x 12V for the power converters).

2.2. DSP-Board

The robot joints communicate via a fiber optical bus system. The standardized SERCOS protocol, which is a real time bus system, is used. The desired and actual motor position, link torque and link position are transmitted every millisecond. Status and supervisory signals like temperatures, voltages and error messages are transferred by means of the acyclic channel, which is defined by SERCOS as well.

The main component of the DSP-Board is a digital signal processor system. A TMS320C31 (60MHz) is used, which can calculate the sophisticated control algorithms within 300ms. Indeed advanced joint torque control is run with 3kHz and artificial joint impedance may be commanded from the Cartesian controller, the only system (a power PC) not integrated into the arm. The input for the controller is either desired position, velocity or torque and the actual motor position, joint position and joint torque. Out of this values the desired motor currents are calculated and transferred to the analog interface by means of a dual port ram.

2.3. Analog Interface

The Analog Interface controls the motor currents and performs the analog/digital conversion of the DC motor supply voltage, motor currents, analog hall sensor signals and the status signals.

We investigated an analog, a microprocessor (digital) and a FPGA (field programmable gate array-digital) realization of the current controller [13].

	analog	digital (processor)	digital (FPGA)
Speed	++	o	+
Flexibility	-	++	+
Simulation Tools	++	o	++
Number of parts	-	o	+

Table 2 decision matrix

The FPGA solution was best according to speed, flexibility, simulation tools and number of desired electronic components. [Table 2]

The AD-interface, the DSP-interface (dual port ram), the PWM-module and the controller core are implemented in one Altera FLEX10K-FPGA. The field oriented current control is calculated in less than 20µs. Via optocouplers the three PWM-signals are connected to the power converter stage.

Fig. 10 shows the functionality of the Anaolg Interface.

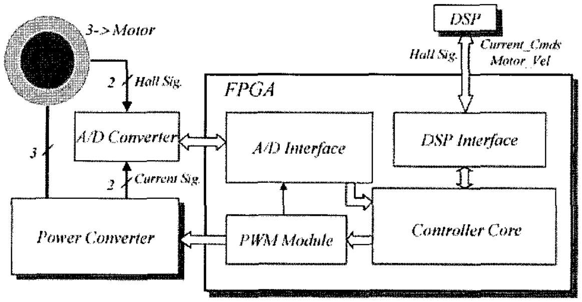

Fig. 10 Functionality of the Analog Interface.

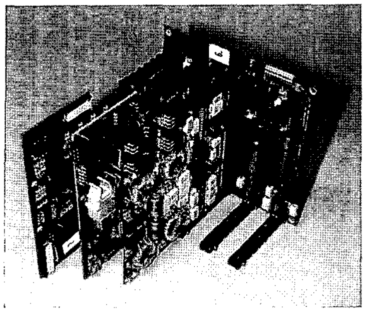

Fig. 11 Analog Interface, DSP-, Supply-Board, Backplane

2.4. Power Electronics

The power electronics has been developed for three-phase motors. The MOS-fets are thermally coupled with the structure of the joint in an ideal manner [Fig. 12]. Two phase currents and the bridge voltage are measured galvanically isolated. A miniaturized, temperature compensated current sensor was developed in our lab. A sophisticated temperature compensation circuit leads to an accuracy of better than 1% over a temperature range from 0°C to 85°C. The size of the whole board is 65mm x 50mm x 25mm.

Features:

- supply voltage	up to 80V
- nominal output current	15A
- switching frequency	40kHz
- nr. of half bridges	3

- two phase currents are measured galvanically isolated
- DC-supply voltage is measured galvanically isolated

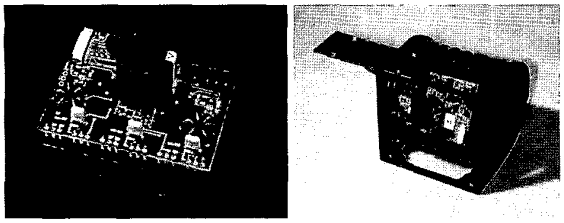

Fig. 12 Power converter Joint 2

2.5. Brushless DC-Motor with Position Sensor

To get a high performance drive unit it is essential that the motor position can be exactly controlled.

Two analog hallsensors are integrated into the motor to measure the magnetic field of the rotor. Thus we were able to meet the challenging space restrictions. The two sensors have a displacement so that their outputs correspond to a sine and cosine signal. With the sine and cosine the motor position is calculated.

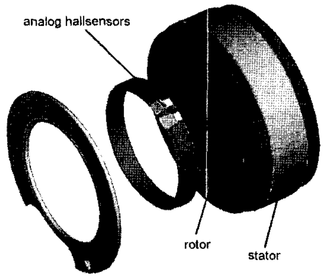

Fig. 13 motor with integrated position sensor

2.6. Safety Brake

Each joint is equipped with a safety brake. An intelligent drive electronics reduces the power dissipation of the brake by the factor of 10. As a result the brake could be redesigned in collaboration with the manufacturer. The total mass went down from 281g to 155g.

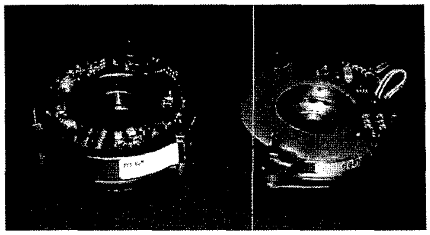

Fig. 14 Original and redesigned safety brake

The control electronics and a limit switch circuit are directly mounted on the brake - another good example for the mechatronics approach.

2.7. Torque Sensor

The deformation of radial beams is measured by strain gauges. The resistance variation of the strain gauges is proportional to the applied torque. By using eight strain gauges temperature effects and transverse forces can be compensated.

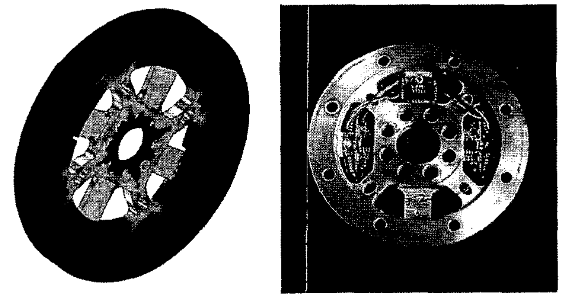

Fig. 15 FEM calculation and real torque sensor

Special efforts were made to find the optimal shape of the beam, the placement of the strain gauges and to make the sensor insensitive to overloads. Four different sensors have been designed with load ranges from 30Nm up to 200Nm. The boards for preamplifying the strain gauge signals are integrated in the sensor mechanics. The mechatronics concept saved space and weight, while the performance of the sensor could be increased.

2.8. Link Position Sensor

The link position sensor is able to measure the off-drive position with an accuracy of 0,01°. As the absolute position is measured no reference sequences have to be performed during the power up of the robot. The sensor has a flat shape and allows the use of a huge hallow shaft. The analog joint position sensor signal as well as the torque signal are digitized and transferred via a serial, high speed, differential communication to the DSP-board.

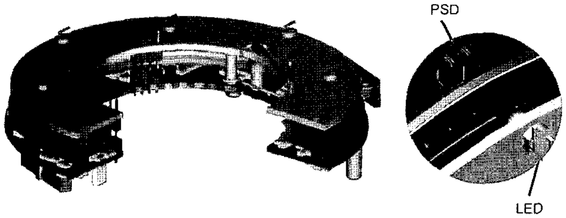

Fig. 16 link position sensor

2.9. Internal Cabling

The cables needed for operating the system are internally fed through the robot. This is especially important for service robots, which should be able to manipulate in obstructed environments. As the light-weight robot does not consume much energy, small cables can be used. The cable tree consists of an AC- and DC-cable, an emergency loop and two optical fibers.

3. Robot control

Considering the application fields for which this robot was designed, a main focus obviously had to be the ability to perform compliant manipulation in contact with an unknown environment. The robot should be able to guarantee the safety of humans interacting with it not only at the TCP, but also along the entire robot structure. This was one of the main motivations for introducing torque sensors in each joint, allowing not only gravity compensation (thus emulating outer space conditions), but also stiffness and impedance control.

Another challenging control problem results from the light-weight design of the robot, which inherently leads to increased joint elasticity. Since the links can be regarded as rigid compared to the joints, a flexible joint robot model can be assumed. This implies a fourth order model for each joint. Therefore, by measuring the motor position q_m and the joint torque τ and by computing the numerical derivatives dq_m and $d\tau$, the complete joint state can be obtained. Our control strategy is to use the available sensors to implement the desired task behavior as well as to compensate the effects of joint elasticity.

The first stage in the controller development was a joint state feedback controller with compensation of gravity and friction [Fig. 17].

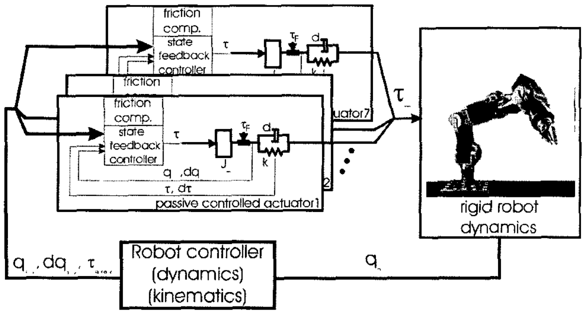

Fig. 17 state feedback controller with gravity compensation

In our opinion, this structure represents; the minimal configuration that can provide both positioning accuracy and effective oscillation damping. The controller constitutes a direct extension of the PD controller still used in most industrial robots to the case of manipulators with joint elasticity. It is proven to be passive and global asymptotically stable for a wide range of parameters [1],[2].

An important feature of this controller structure is that, by a suitable parameterization, it can be used to provide a position, a torque, as well as an impedance controller. In fact, the position and the torque controllers are implemented as special cases of the impedance controller, for maximal and zero stiffness respectively. The gains are computed online, to provide the desired joint stiffness and damping. The state feedback controller is implemented in a decentralized manner on the signal processors in each joint, with a high sampling rate (3kHz).

Using joint parameter identification and CAD modeling of the rigid robot components, an accurate robot model was obtained, which was subsequently used for the design and simulation of model based controllers [2].

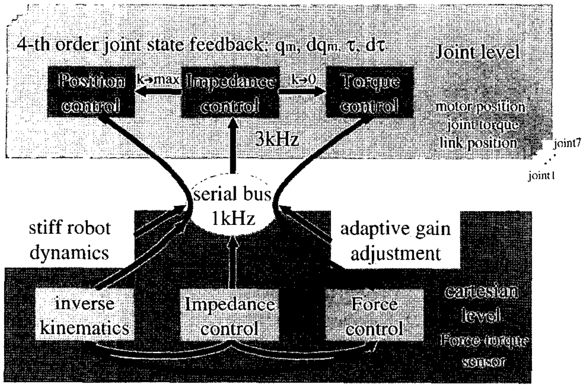

Fig. 18 controller architecure

There exist many powerful theoretical results concerning the position control of flexible joint robots. They include singular perturbation and integral manifold [14],[8],[12], feedback linearization [14] and dynamic feedback linearization [4], passivity based and adaptive control methods [15],[3]. Their practical implementation is problematic due to the complex computations, the high derivatives of the signals or the accurate model parameters required. Nevertheless, the proposed controller structure can be extended to implement simplified versions of some of these controllers.

A first extension of the controller structure in Fig. 17 uses the full robot dynamics for the controller design. Subsequently, the controller gains are adjusted online, taking into account not only the desired stiffness and damping, but also the variable link inertia for each joint.

The rigid robot dynamics and the Cartesian level control are computed on a power PC that is connected to the joint controllers through a serial connection with a 1ms sampling rate. The robot constitutes an optimal platform for testing and comparing various Cartesian control methods, by accessing one of the three interfaces on joint level [Fig. 18]. For instance, to implement force control, one can directly access the joint torque interface or alternatively, use the inverse kinematics and access the joint position controller. In the same way we implemented Cartesian stiffness control based on each joint controller. Although from a theoretical point of view one may expect similar results with the various methods, in practice the performance proved to be different due to effects such as model errors, friction and sampling rates. Therefore, it is the specific task that dictates the most efficient approach. Generally it is useful to choose the solution that requires maximal bandwidth in the joints and minimal bandwidth in the Cartesian task.

The Cartesian position control uses a singularity robust inverse kinematics module for redundant manipulators. It enables collision avoidance and the optimization of additional task dependent criterions [9],[10],[11].

4. Summary and outlook

The new DLR light-weight robot represents a major step towards a new light-weight robot generation. The design has led to a virtual prototype of the robot which provides important control parameters and allows to integrate electronics efficiently into the arm.

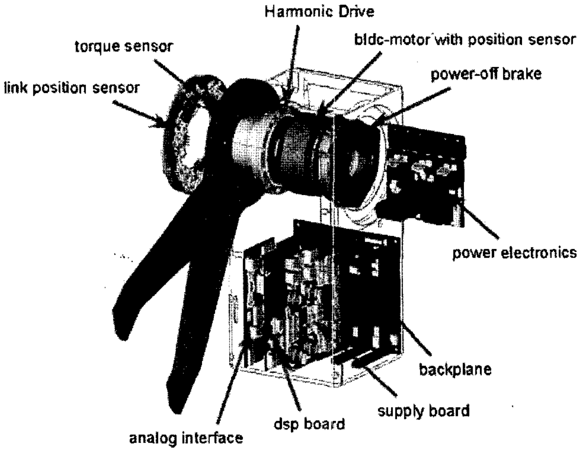

Fig. 19 The intelligent joint

This way, all power and joint electronics have been integrated into an intelligent joint [Fig. 19]. The manipulator has increased flexibility due to optimized 7 dof kinematics. Together with consequent light-weight construction this mechatronic approach made a weight to payload ration of 17 to 8 possible. The integrated joint torque sensors enable the implementation of advanced control methods for force control, vibration damping and stiffness control.

Our next steps try to continuously reduce weight by using a self-developed, specialized external rotor motor, a new piezo brake (weighting only 30g), more carbon fiber technology and higher joint modularity. As a central goal we try to further optimize the joint performance index I as defined an proposed in [7].

Acknowledgement

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