The Modular Multisensory DLR-HIT-Hand: Hardware and Software Architecture

Hong Liu, *Member, IEEE*, Peter Meusel, Gerd Hirzinger, *Fellow, IEEE*, Minghe Jin, Yiwei Liu, and Zongwu Xie

***Abstract*—This paper presents hardware and software architecture of the newly developed compact multisensory German Aerospace Research (DLR)-Harbin Institute of Technology (HIT)-Hand. The hand has four identical fingers and an extra degree of freedom for the palm. In each finger, there is a field-programmable gate array (FPGA) for data collection, brushless dc motors for control, and communication is accomplished with palm's FPGA by point-to-point serial communication (PPSeCo). The kernel of the hardware system is a peripheral component interconnect (PCI)-based high-speed floating-point DSP for data processing, and FPGA for high-speed (up to 25 Mb/s) real-time serial communication with the palm's FPGA. In order to achieve high modularity and reliability of the hand, a fully mechatronic integration and analog signals *in situ* digitalization philosophy is implemented to minimize the dimension and number of the cables (five cables including power supply), and protect data communication from outside disturbances. Furthermore, according to the hardware structure of the hand, a hierarchical software structure has been established to perform all data processing and the control of the hand. It provides basic air position indicator (API) functions and skills to access all hardware resources for data acquisition, computation, and teleoperation. With the nice design of the hand's envelop, the hand looks more like a humanoid.**

***Index Terms*—Dexterous robot hand, DSP, field-programmable gate array (FPGA), modular.**

I. Introduction

The DEVELOPMENT of dexterous robot hand is a very challenging endeavor that has been pursued by many researchers. Many dexterous robot hands have been built over the past three decades [1]–[5]. These devices make it possible for the robot to grasp and manipulate objects.

Since 1997, German Aerospace Research (DLR) has developed two generations of multisensory dexterous robot hands: DLR Hand I [6] and II [7]. Both hands are highly integrated multisensory mechtronic hands. Based on the experience of DLR Hand I, the DLR Hand II was designed to be stronger and more reliable. The number of cables between the hand and main microprocessor has been greatly reduced from more than 400 to only 12. The optimal combination of brushless dc (BLDC) motors, harmonic drives, belt transmission, and differential bevel gear transmission makes the fingertip force up to 30 N. The extra degree of freedom of thumb enables the hand not only for power grasping but also for fine manipulation. It is well recognized that the DLR Hand II is one of the best robotic hands in the world. On the other side, however, because of its high integration, it is not easy to manufacture such a hand, especially for the actuator system, where all the motors are specially designed and the analog hall sensors must be adhesived and calibrated carefully. Since 2001, based on the experience of DLR Hand II, Harbin Institute of Technology (HIT) and DLR jointly developed a modular four-finger dexterous robot hand: the DLR-HIT-Hand [8] (see Fig. 1, left). Fig. 1 (right) shows the hand after a nice envelop. The goal of the project is to build a smaller robot hand than DLR Hand II, and in the near future, the hand can be manufactured in a small series. The total price should be as low as possible and the performance must be as high as possible. Instead of the expensive Versa Module Eurocard (VME) bus board, a peripheral component interconnect (PCI)-based DSP/FPGA board has been developed successfully. The amount of cables was reduced from 12 in DLR-Hand II to 5 by introduction of half-duplex low-voltage differential signaling (LVDS). Also, the actuators are all commercially available brushless dc motors, and the joint angles are measured by noncontact Hall sensors instead of potentiometers.

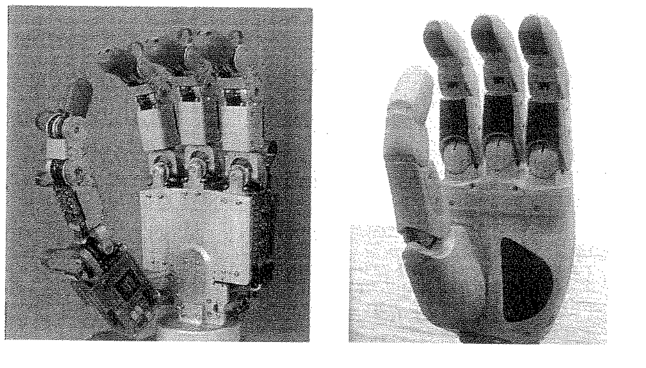

Fig. 1. DLR-HIT-Hand.

The paper is arranged as follows. Section II gives an overview of the DLR-HIT-Hand. Section III describes the multisensory system of the hand. Sections IV and V present the hardware and software architecture, respectively. Conclusions and future work are addressed in Section VI.

II. Overview of the DLR-HIT-Hand

The DLR-HIT-Hand is a multisensory and integrated four-fingered hand with in total 13 DOFs, as shown in Fig. 1. To achieve a high degree of modularity, all four fingers are identical. Each finger has 3 DOFs and four joints, the last two joints

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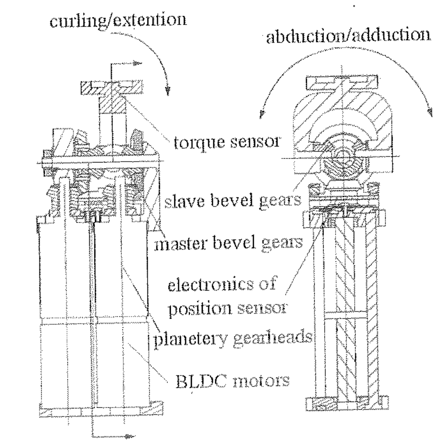

Fig. 2. Finger base joint.

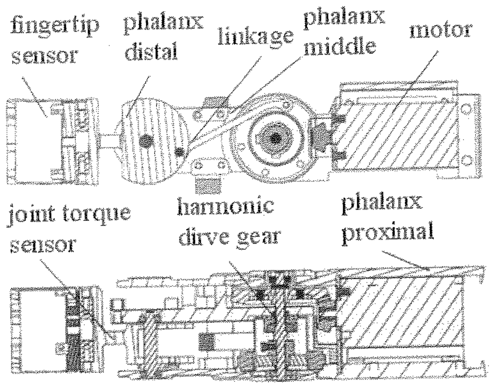

Fig. 3. Finger unit with a BLDC motor.

are mechanically coupled by a rigid linkage. The thumb has an additional DOF to realize the motion relative to the palm. All actuators are integrated in the finger's base or the finger's body directly, the electronics and communication controllers are fully integrated in the finger's base in order to realize modularity of the hand and minimize weight and amount of cables needed for a hand. In order to save the work for special motors assembly with adhesive and calibration of analog Hall-effect sensors, appropriate commercial BLDC motors with the power for 10 N fingertip force have been selected. The motor measures 16 mm in diameter and 28 mm in length. There are eight cables including three drive signals, three analog Hall sensors, and corresponding power and ground.

The finger of the DLR-HIT-Hand consists of two independent parts: base joint unit with 2 DOFs and finger unit with 1 DOF and two joints (Fig. 2). Because the effectiveness of bevel gear differential transmission has been successfully demonstrated in the DLR Hand II, it has been adopted in the base joint design. The planetary drive gears with reduction ratio 159:1 are directly coupled to the BLDCM (Fig. 3), and the bevel gears are connected to planetary gears via additional gear reduction of 2:1. For curling/extension motion, the motors apply a synchronous motion to the bevel gears using the torque of both motors. For abduction/adduction motion, the motors turn in contrary directions. This causes a curling motion on the fingertip using the

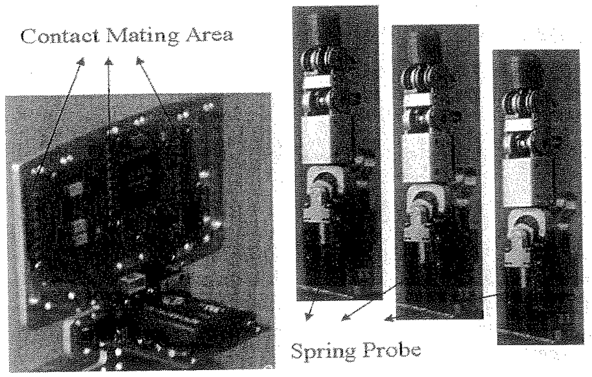

Fig. 4. Modular fingers and palm.

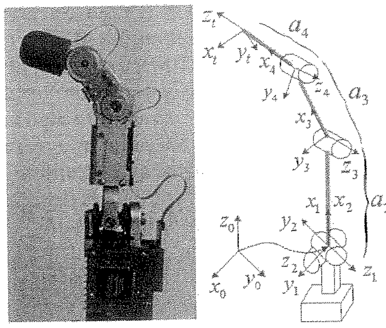

Fig. 5. Finger kinematics.

torque of both motors and means that we can use small motors and reducers while reaching double output force on the fingertip. The middle link is actively actuated by a BLDCM in combination with a tiny harmonic drive gear. The harmonic drive with reduction ratio 100 : 1 measures 20 mm in diameter and 13.4 mm in length. The motions of middle phalanx and distal phalanx are not individually controllable; they are connected by means of the rigid linkage, whose structure and parameters are optimized by simulation. Kinematics design of a multifingered robot hand shows that the motion of the thumb and the fourth finger is absolutely necessary to improve the grasping performance in case of precision and power grasp. Therefore, the hand will be designed with an additional DOF in order to realize motion of the thumb relative to the palm. This enables use of the hand in different configurations.

All of the four fingers are modular and identical. They can be easily fixed to the hand's palm, as shown in Fig. 4. Instead of electrical connectors that need more space, several spring probes are chosen to connect the fingers with the palm electrically. With four screws, one finger can be easily and robustly fixed to the palm. Also, the structure of the palm is designed to build the left hand or right hand easily for different applications.

The kinematics definition for one finger is shown in Fig. 5. The D-H parameters of the finger are given in Table I.

III. Multisensory System

A dexterous robot hand needs as a minimum a set of force and position sensors to enable control schemes like position control and impedance control in autonomous operation and

TABLE I
D-H PARAMETERS

Joint angle (deg)		Length(mm)	
θ_1	$[0 \quad 90]$	α_1	0
θ_2	$[-20 \quad 20]$	α_2	67.8
θ_3	$[0 \quad 90]$	α_3	30.0
θ_4	$[0 \quad 90]$	α_4	29.5

TABLE II
SENSOR EQUIPMENT OF ONE FINGER

Sensor type	Count/finger
Joint torque	3
Joint position	3
Motor position	3
Force/torque	1
Temperature	2

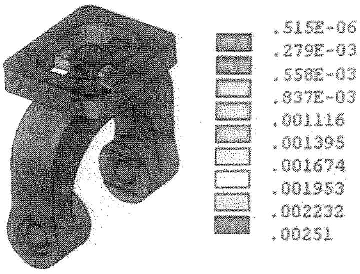

Fig. 6. Base joint torque design.

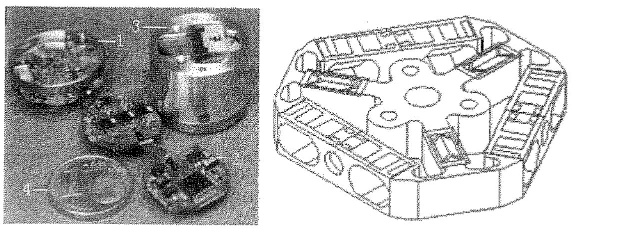

Fig. 7. 6 DOF fingertip sensor and its structure.

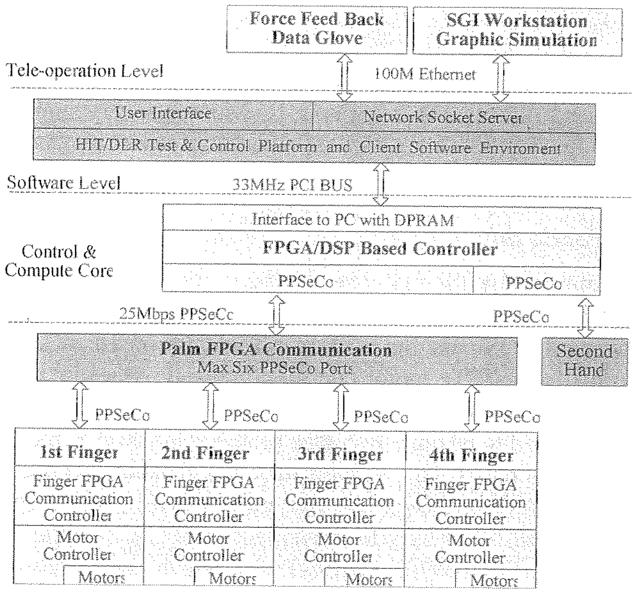

Fig. 8. Controller architecture of the DLR-HIT-Hand.

teleoperation. Compared to DLR Hand II, there is some improvement in the sensor system. Instead of contact potentiometer in each joint a contactless Hall-sensor-based joint position sensor has been developed. Also, base joint torques have been designed in flat form so that the whole height could be reduced. Sensor equipment of the DLR-HIT-Hand is given in Table II.

Each joint is equipped with a strain-gauge-based joint torque sensor. To reduce the length of a finger, a new type base joint torque sensor with 2 DOFs has been developed (Fig. 6). The torque sensor located in the middle joint is integrated into the connecting part and can precisely measure the external torque.

Since we can calculate the joint position from the motor Hall sensors, the joint position sensor would not be absolutely necessary. However, in the presence of the elasticity and hysteresis of the transmission system, the joint position sensor can provide more accurate information of the joint position, and it can eliminate the necessity of referencing the fingers after power up. A new integrated two-axis Hall-effect sensor, replacing conventional contact potentiometer and contactless incremental encoder, is integrated into every active joint of the DLR-HIT-Hand in order to measure the joint position and meet the requirement.

A miniaturized six-component force/torque sensor [20 mm in diameter and 16 mm in height (Fig. 7)], with full digital output has been developed for the fingertip. It needs only six wires including power supply for the high-speed data transmission (15.6-kHz sampling frequency). Based on a former design, the elastic body is made from only one part and all strain gauges are on one surface (Fig. 7, right), rendering the sensor extremely flat and very appropriate for thin-film technology of strain gauges for easier assembly. A signal processing circuit and high-speed serial analog-to-digital (A/D) converter (12 b) are also integrated in the sensor. The force and torque measure ranges are 30 N and 600 Nmm, respectively. Also, a 200% mechanical overload protection is provided in the structure.

IV. HARDWARE ARCHITECTURE

The recently developed DLR-HIT-Hand is controlled by a multiprocessor controller based on FPGA/DSP. Fig. 8 gives an overview of the hardware and software architecture of the whole control system. In order to minimize cabling and weight of the DLR-HIT-Hand, a fully mechatronic design philosophy is introduced to develop the hardware system. All the analog signals are converted *in situ* into digital signals, and serially transmitted into palm FPGA board and further to a PCI-based central processor. The hardware system consists of the PCI-based DSP/FPGA board configured as a master, and palm FPGA board and four-finger FPGA boards configured as a slave. The main tasks performed by the master board are task management, computer-intensive calculation, and interface with PC. The slave boards are responsible for the interface functions with the real world, such as pulsewidth-modulation (PWM) signal generation, interface to analog-to-digital controller (ADC), etc. Communication between the master and the slave is fulfilled by

TABLE III
DATA PACKAGE OF PPSeCo

Name	SOP	ADD	DATA	CRC 16	DUMMY
Example	"0 0000 001"	"0 0011 000"	"001100000101 1000" + ... + "0111001001010001"	"011 000000 110111 "	"10100 11001001 1"
Explain	Start of Package	Address	Data	CRC Check Sum of Package	Dummy

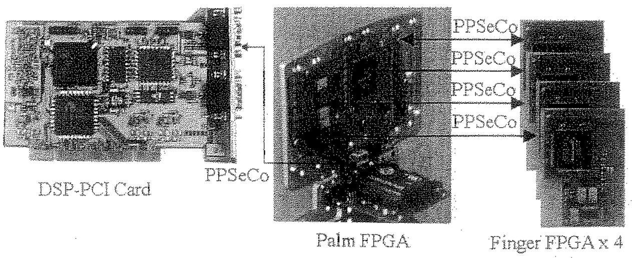

Fig. 9. DSP/FPGA hardware components.

the Palm FPGA at a speed of up to 25 Mb/s. It is very simple to implement because both devices have this protocol integrated.

A. PPSeCo Bus

To implement the real-time feedback control of the dexterous robot hand, a large amount of data needs to be transmitted between the DSP and the hardware. The data consists of sensor information and the motor control commands. Because of the large amount of data the communication between the FPGA and the DSP need to be quite fast. One probable interface is the universal serial bus (USB), which, today, is a standard interface in PC. The USB interface is very fast, up to 12 Mb/s, but it is quite complex and is not easy to implement in FPGA. Another fast interface is FIRE-WIRE (IEEE-1394), which has bandwidths over 1 Gb/s. However, FIRE-WIRE is not yet common in regular computers and is also very complex to implement. Parallel communication is another interface, which is quite fast, easy to implement, and uses only a small part of the FPGA, but it needs many cables. So, in order to integrate the DLR-HIT-Hand freely to any robot system, i.e., increase the transmission speed and reliability of data communication, and reduce cabling and noise in sensor signals, a point-to-point high-speed serial communication (PPSeCo) system was designed for the data communication between the finger and the hand, and the hand and the DSP/FPGA board. It can handle the communication needed to pack all digital sensor values from lower control level and distribute command signals to each finger. In order to realize these requirements, PPSeCo should have the following characteristics.

1) PPSeCo is composed of a point-to-point, half-duplex, and serial communication link, based on LVDS for the physical layer.
2) PPSeCo uses a 16-b cyclical redundancy check (CRC) checksum based on the Comité Consultatif International Téléphonique et Télégraphique (CCITT) polynomial $x^{16} + x^{12} + x^5 + 1$ (the same function used by the Xmodem protocol) to ensure that the majority of communication errors can be detected.
3) Non-return-to-zero inverted (NRZI) data encoding and automatic bit stuffing/stripping are used for data encoding.
4) Variable baud rate (typically 25 Mb/s).
5) Uses communication scheme based on packet transfer and error correction. Packet structure is shown in Table III.

For data transmission, the serial communication system (PPSeCo) has been implemented on a PCI board, and the palm and the finger of DLR-HIT-Hand. All communication and other control programs for all FPGAs are written in VHDL and run on FPGAs. With this communication technology, the external cables of the DLR-HIT-Hand have been reduced from eight in DLR Hand II to three, with one ground line and two differential communication lines.

B. DSP/FPGA PCI Board

The main controller of the DLR-HIT-Hand is a Texas Instruments (TI) floating-point DSP TMS320C6713 with maximum 1350 mega floating-point operations per second (MFLOPS). Some characteristics of this board are as follows: 225 MHz clock, float point arithmetic unit, 32 MB synchronous dynamic random access memory (SDRAM), 512 KB flash program memory, and 16 K dual-ported RAM. It is a high-performance embedded processor system that is able to operate stand-alone as well as a slave component. According to the high performance and unique hardware structure of the DSP, it is an optimal alternative to realize complex control algorithms and very fast computation easily; thus, the board is an excellent choice for multichannel communication and multifunction application. Furthermore, the DSP board provides a series of peripherals that make it easy for the designer to access and extend the hardware resources.

Based on the DSP, a PCI-based DSP/FPGA board was designed (as shown in Fig. 9, left). The PCI board exchanges data with PC via a PCI bridge controller. At the same time, the board communicates with the palm FPGA via PPSeCo achieved absolutely by the way of hardware. On the PCI board, DSP and FPGA achieve data exchange via a fast parallel interface. All high-level data processing is implemented on the DSP board, the DSP mainly plays the role of a computing unit for complex control algorithms because of its high-performance floating-point capabilities. Also, the FPGA communicates with external components from the PCI board via a serial interface. The FPGA converts serial signals from the palm FPGA to parallel signals and transmits them to the DSP via the parallel interface and *vice versa*.

Furthermore, the DSP/FPGA PCI board communicates with the PC via a 33-MHz PCI bus and provides two PPSeCo interfaces for two independent palm FPGA communication controllers to control two hands simultaneously or control one hand and one robot arm.

C. Palm FPGA Board

The palm FPGA board (in the middle of Fig. 9) performs data transmission between the finger FPGA and the DSP/FPGA PCI board via the PPSeCo communication system. The command signals received from the DSP/FPGA PCI board are first stored in the buffer of the palm FPGA and then distributed to each finger FPGA. In other ways, the sensor information received from the finger FPGA is also stored in the buffer of the PCI board first, then the palm FPGA packs them to data package in some way and transmits it to the DSP/FPGA PCI board. The palm FPGA reads the information from the four-finger FPGA boards through a synchronization approach with the system clock. All of the receiving and transmission operations could be finished in 200 μs; the 200 μs sampling period is determined by the motor's Hall sensor readings and joint angle calculations. The palm FPGA provides a maximum of six PPSeCo ports, one is for the PCI board, four ports are for the four-finger-FPGA boards, and the last is reserved.

The DLR-HIT-Hand's thumb has an additional DOF to imitate the same motions of a human's thumb. The extra DOF is actuated by a brush dc (BDC) motor, and its driving circuitry based on monolithic BDC motor controller is integrated in the palm FPGA board. In most cases, the thumb location in either of the two limit positions is determined by mechanical methods and is detected by optical-coupler-based limit switches. In our hand, an extra potentiometer has been integrated for more flexible orientations of the thumb instead of only two limit ones.

Furthermore, dc/dc converter-based power supply for all fingers is also integrated in the palm FPGA board. It provides power for all analog circuitry, including the finger FPGA boards, the BLDC motor driving boards, and all sensor signal processing boards.

D. Finger FPGA and BLDC Motor Board

One major goal of the hand design is to fully integrate all the necessary electronics and actuators in the fingers and the palm of the DLR-HIT-Hand. The fully integrated concept is helpful for the hand to achieve high-degree modularity and to reduce the whole size of the hand so that the DLR-HIT-Hand's size would approximate to that of a human's hand. There are four-finger modules (as shown in Fig. 10, right), each finger module integrates the finger FPGA, the BLDC motor board, and the sensor boards together, and one finger module is an independent subsystem of the hand. The electronic hardware architecture of one finger module is shown in Fig. 10 (left).

The finger FPGA board is responsible for information management and data processing inside the finger module. The fully digital sensor signals output from the sensor boards are just numeric values without any physical meaning, so they cannot be used directly in control algorithms. The finger FPGA converts them into physics dimensions of joint's angles and velocities through sensor calibrations, and packs them into a data package containing original information of the sensors, which, in turn, will be transmitted to the palm FPGA board via the PPSeCo system. The connection between the finger FPGA board and the BLDC motor board is realized through general board-to-board interface.

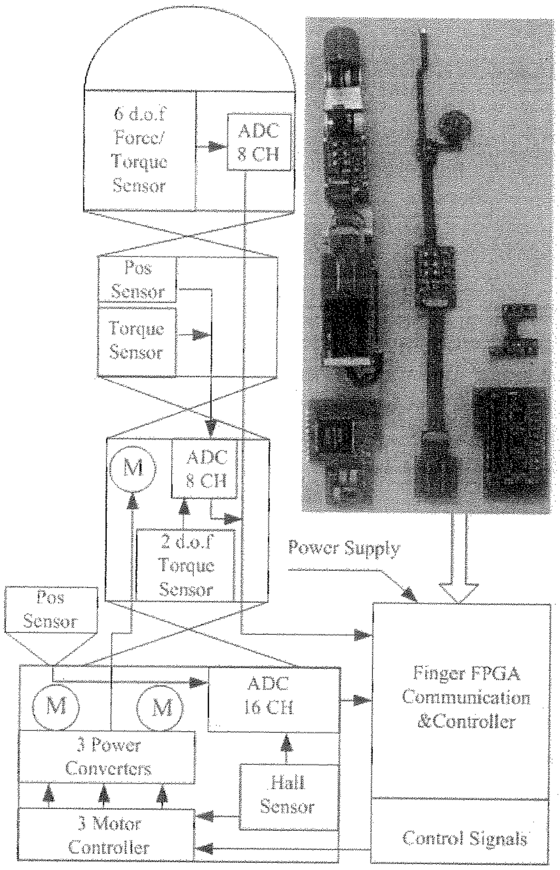

Fig. 10. Electronic architecture of one finger module.

The BLDC motor is chosen as a driving component for the DLR-HIT-Hand. In order to decrease the area of the BLDC motor board, a monolithic BLDC motor controller with high-side drive circuitry is selected to construct the driving circuitry with power electronics. The BLDC motor board for three motors of one finger measures 35 mm $\times$ 65 mm that makes it easy for the motor board to be integrated into the finger module. On the other hand, a flexible printed circuit board (PCB) has been designed to reduce the connectors needed for the multisensors, the PCB can move through the joints of each finger and link sensors and FPGA (see Fig. 10, right) together. In each finger, four ADCs with eight-channels and 12-b resolution convert analog sensor signals into digital serial signals as close as possible to the sensor resources; then, there is only digital data to cross any joint of each finger.

V. SOFTWARE ARCHITECTURE

Based on the hardware structure of the DLR-HIT-Hand, the software architecture has been developed according to the principle of multilevel structure and modularity. As shown in Fig. 11, all data processing and control algorithms of the hand are realized in five levels. In *lower control level*, sensor data acquisition and motor actuation are implemented by finger FPGA. The *data process level* performs all data processing and communication

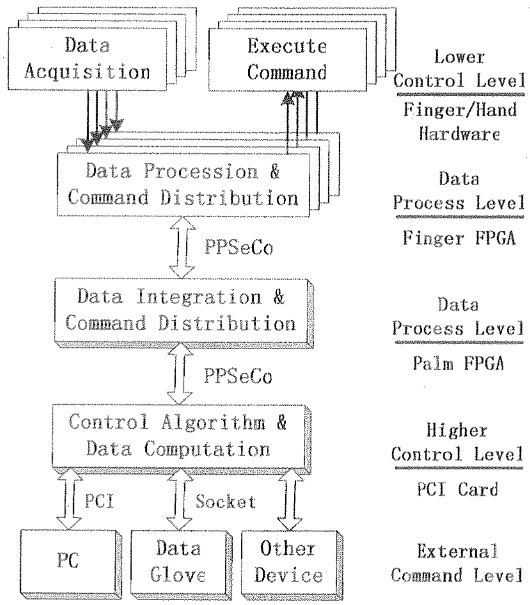

Fig. 11. Software architecture of DLR-HIT-Hand.

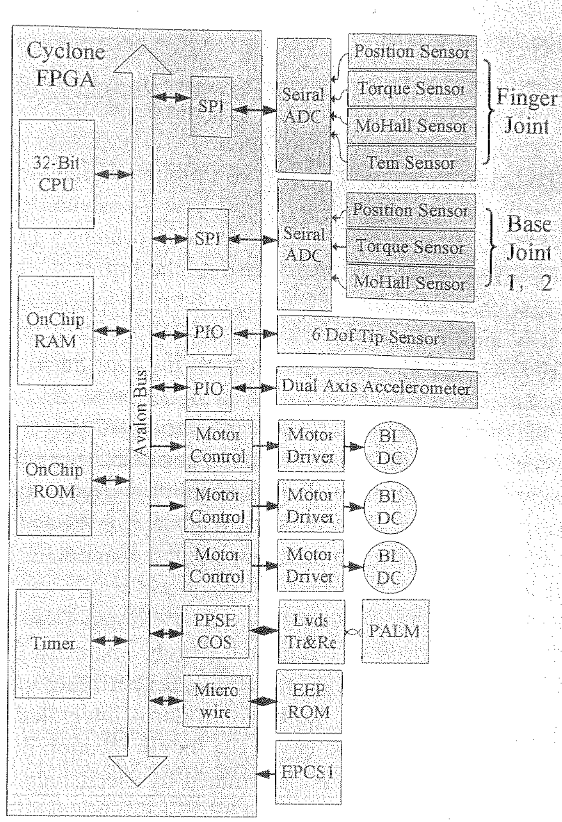

Fig. 12. Finger FPGA architecture.

needed to pack all digital sensor values from *lower control level* and distribute command signals to each finger. The *higher control level* implements all computation for the hand and provides basic client interface for *external command level*, such as the PC and data glove.

A. Lower Control Level

FPGAs are very flexible for implementing hardware systems. A compact FPGA module has been developed based on the Cyclone FPGA (5980 LEs) from Altera. The implementation is a mixed hardware and software design. It allows to design system on a chip (SoC) module, mixing hardware and software. These tools provide a synthesizable 16 and 32 bit CPU (called Nios) and several peripherals are readily available [e.g., universal asynchronous receiver transmitter (UART) or serial peripheral interface (SPI) communication controllers, parallel input/output (I/O)]. The hardware contains mainly the interface to serial ADC, motor controller, electrically erasable programmable read-only memory (EEPROM), etc. The software (executed in the Nios CPU) takes care of combining all the modules and data processing, such as calculating joint angle, motor speed, and signal filter. Some key features were taken into account in the realization of the controller. First of all, FPGA implementation leads to a compact and modular control board that can be mounted close to the hand in order to reduce cable routing through the structure and simplify system documentation and maintenance. Another reason for the choice of FPGA implementation is the possibility of field-reprogramming the controller, allowing future upgrading of the system. The FPGA-based low control level is shown in Fig. 12. The function of each part is described in the following sections.

1) Soft CPU: Altera's Excalibur with the Nios soft core embedded processor has been chosen as the core of the lower control system. The Nios CPU core provided the logic for both the system processor and additional units designed in C and VHDL. The logic blocks implemented on the Nios board consisted of a basic driver or state machine coordinated with the processor, peripheral interface, and data processing.

2) Memory and On-Chip Bus: The flash memory contains the configuration of the FPGA, used on power-up or reset. It can also store user data or executable files. RAM and ROM on-chip can be used for program and data memory. An on chip bus called Avalon bus is used for connecting on-chip processors and peripherals together into a system-on-a-programmable chip (SOPC). The Avalon bus is an interface that specifies the port connections between master and slave components, and specifies the timing by which the components communicate.

3) Microwire Interface to EEPROM: Calibration parameters for sensors vary in between sensors as well as between fingers. To maintain modularity and exchangeability of hardware, these parameters are stored in the individual fingers themselves. Therefore, each finger is equipped with an EEPROM to store the parameters for the corresponding finger. Upon powering up the system, the parameters are read. The FPGA implements the Microwire interface to serial EEPROM.

4) SPI Interface to Serial ADC: In order to increase the reliability and minimize the amount of cables, we chose the serial ADC with eight channels and 12 b resolution to convert the sensor signals as near as possible to the sensor that moves through digital data in each link. Thus, only digital data are crossing any joint of the finger. The SPI on the serial ADC is configured for the slave mode. The Nios SPI peripheral is four-wired and can be used as a master device. It allows software to communicate with one or more external devices over an SPI bus. The software controls and communicates with the SPI peripheral through five memory-mapped, 16-b registers accessed by a standard Nios peripheral bus connection. The clock of the communication can be set to 2 Mb/s.

5) IO Interface to Dual-Axis Accelerometer: We use dual-axis accelerometer to get the dynamic acceleration (e.g., vibration) and static acceleration of the finger. Also, the Nios CPU uses the force of gravity as an input vector to determine orientation of the finger in space. The outputs are digital signals whose duty cycles (ratio of pulsewidth to period) are proportional to the acceleration in each of the two sensitive axes. The Nios parallel input/output (PIO) module implements the interface to accelerometer and calculates the posture.

6) Arithmetic and Data Processing: Some simple arithmetic and data processing are implemented by Nios CPU, such as calculation of the joint angle from the position sensor, calculation of the motor speed from the motor Hall sensor, joint angle limit protection, low-pass filter for raw sensor, etc. Measurements from two Hall sensors $\tilde{A}$ and $\tilde{B}$ measuring the magnetic field 90° apart can be computed according to

$$\theta = \arctan\left[\frac{\alpha(\tilde{A} - \bar{A})}{\beta(\tilde{B} - \bar{B})}\right]$$

with $\bar{A}$, $\bar{B}$ being the mean value of the respective signals and α, β are the correcting factors for amplifier. We can get the motor angle using the same way. The velocity signal of the joint is obtained by using finite differential of the position signal. The special base joint of DLR-HIT-Hand requires at least joint limitation violation checks, because workspace limitations have to be tested in true joint angles rather than the directly measurable motor or transmission angles. Joint and motor angles are related through a coordinate rotation. Through this rotation, the easily testable rectangular workspace in joint coordinates is represented by a polygon in motor coordinates. A digital low-pass filter, which is implemented by Nios CPU, eliminates unwanted high-frequency noise of each raw sensor signal.

B. Data Process Level

The *data process level* consists of finger FPGA, palm FPGA, and PCI FPGA levels. One of the most important functions of the level is to exchange digital sensor and command data for all fingers. The command signals for controlling the motors received from the DSP/FPGA PCI board are first stored in the buffer of the palm FPGA, and then distributed to each finger FPGA. On the contrary, the preprocessing sensor information received from the finger FPGA is also stored in the buffer of the palm FPGA first, then the palm FPGA packs them to data package in some way and transmits it to the DSP/FPGA PCI board. Therefore, all four-finger sensor data and motor command together are synchronized and coordinated by the palm FPGA.

In each finger FPGA level, the calibration parameters for all sensors of each finger are different and stored in the related FPGA's memory. Furthermore, the finger FPGA and palm FPGA work together to calculate the joint angles, joint torques, and fingertip force/torque information. Based on this information, the FPGAs will provide a quasi-hardware protection for the mechanical and electronic hardware from being damaged when some unexpected operations happen. On the other hand, an additional low-level controller written in VHDL has been implemented in FPGA, and it provides a simple PID control with sufficient computational power to realize joint position and torque control for each finger. The parameters of the PID controller can be configured online via *PC platform* and the platform can online adjust more than 256 control parameters simultaneously.

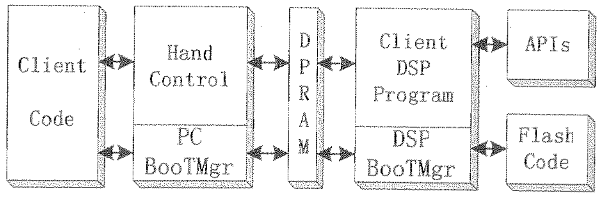

Fig. 13. Software architecture of higher control level.

The finger FPGA level provides two control modes: *direct control mode* and *advanced control mode*, which are triggered by the control flag. In the *direct control mode*, the finger FPGA receives the command information about direction, brake, and PWM from the palm FPGA and distributes it directly to the BLDC motor driving circuitry. In the *advanced control mode*, the data from the palm FPGA is the desired joint angle, compliances, joint torques, or fingertip force, and will be processed via the finger FPGA to control BLDC motor's directions, brakes, and PWM signals.

C. Higher Control Level

In this level, basic API functions and computation skills are provided for data processing and complex control algorithms. In most cases, all sensor data are converted (such as position and velocity computation) by DSP according to some special principles; at the same time, all command signals are transmitted to the *data process level.*

As shown in Fig. 13, the higher control level performs almost all control tasks of the DLR-HIT-Hand. The software architecture of the level exchanges all data between the PCI board and PC, and it mainly consists of three parts: boot manager, PC platform, and API functions.

The boot manager consists of the DSP boot manager and PC boot manager, as shown in Fig. 13, and it manages all control programs for the hand. When DSP is reset or powered ON, the DSP hardware will load DSP boot manager from flash memory, and then, the boot manager controls the whole DSP. When the PC boot manager detects that DSP boot manager is running, it communicates with the DSP boot manager to implement some basic tasks such as loading the client DSP program to SRAM. After the client DSP program is loaded and executed, it controls the whole DSP resources except some reserved space of external SRAM, and the DSP boot manager will only control DSP when it is needed. This software mechanism induces programmers not

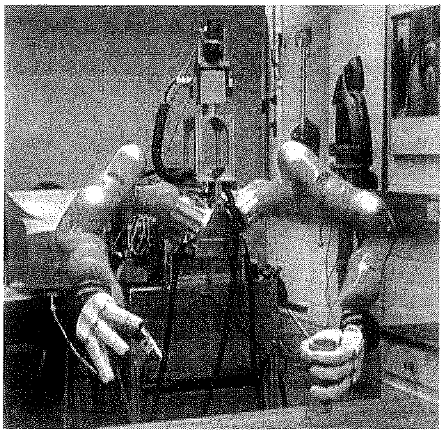

Fig. 14. Hands on a double-arm humanoid robot prototype.

to care about the functions of SRAM and other DSP peripheral resources at all.

API function of the hand is a set of DSP subroutines that helps the programmer to access all hardware resources for sensor data acquisition, read/write data of DSP's external memory, etc. The *API function* distinguishes the hand controller from other hardware systems and just focuses on the control algorithm itself. The *API function* consists of the hand interface, PC interface, DSP peripheral interface, and basic algorithm APIs. API functions provide all necessary low-level interfaces to the DSP, hand controller, and PCI bridge controller. With these functions, programmers need not care about how the low-level hardware works. A client/server interface is designed to construct communication with force feedback data glove and graphic workstation via a 100 M Ethernet. Programmers can also design a special control strategy based on these API functions to test and control the hand or achieve teleoperation by the data glove.

In order to provide a friendly client interface, a *PC platform* is developed based on the *PC boot manager.* The *PC platform* is a detailed graphics and numerical interface to monitor and display almost all states of the hand during test and control tasks. It can also control and test each finger directly. All original sensor signals are calibrated before application of the control algorithm. The *PC platform* can perform the calibration in minutes with the parameters of all the sensors stored in finger FPGA. It is important to supervise the behavior of the client program in real time, but in most cases, there is no DSP hardware debugger for programmers to debug their control programs. The *PC platform* provides interfaces to track some interesting local variables of the program and watch its running state.

D. External Command Level

In most control tasks, user attention is usually needed to control the DLR-HIT-Hand in real time according to a special situation or achieve teleoperation via the data glove. The external level provides interfaces to connect with the *higher control level* and distributes such control instructions. Furthermore, a graphic workstation can be connected through Ethernet to display the state of the hand in visual environment.

VI. Conclusion and Future Work

This paper has presented a high-performance hardware and software architecture for a new generation dexterous robot hand. With this basic architecture, many control applications for the hand have been successfully demonstrated such as music playing, autonomous grasping of a bottle, and teleoperation experiments. The hand has been successfully used in several research projects, such as the German humanoid project DESIRE, as shown in Fig. 14. Future work will be concentrated on the optimal grasping planning and multifinger coordinated control. Also, a smaller five-finger dexterous robot hand is under development.

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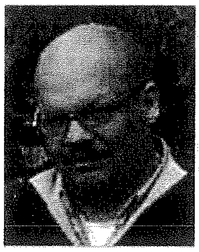

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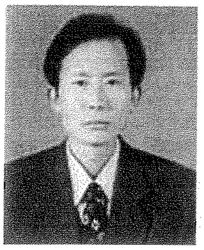

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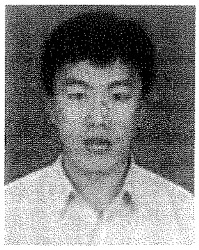

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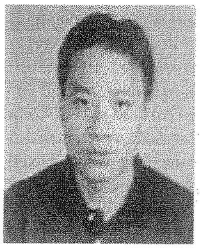

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