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DSP/FPGA-based Highly Integrated Flexible Joint Robot

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***Abstract*—This paper presents a DSP/FPGA based multi-sensory flexible-joint robot including modular mechanics, hardware and software architecture. The robot is composed of four modular flexible joints and a DLR-HIT-Hand. In each joint there is a Field Programmable Gate Array (FPGA) for sensor data processing, brushless DC motor control and communication. The kernel of the hardware system is a PCI-based high speed floating-point Digital Signal Processor (DSP) for the arm/hand Cartesian level control, and FPGA for two high speed (up to 25 Mbps) real-time Serial Buses communication with the arm and hand. All the electronics are integrated into the joint to achieve the high modularity and reliability. Cartesian impedance control and position control with on-line gravity compensation are realized for regulation tasks of the robot with elastic joints. In addition, the experiments of the joint impedance control and Cartesian impedance control demonstrate that the multi-sensors highly integrated robot has a good performance.**

I. INTRODUCTION

Robot arms, designed for industrial applications, traditionally are treated as mechanical multi-body systems, where several rigid bodies are connected by actuated joints. In the past few years the robotics community evolved growing interest in robots which are designed for operation in the space or hazardous environment and aimed towards autonomous operation with dexterous manipulation and mobility [1-5]. For this kind of applications, the robotics systems are desired to be built up compact, light weight and high force controllable.

In 2003, HIT-DLR lab has developed a two-joint robot arm prototype. There are some problems existed in this prototype. Firstly, the cables for communication and power often twisted; secondly, the joint torque sensor couldn't protect itself from overload; thirdly, the 2-axis hall sensor couldn't provide high precise joint position information, and all. Based on the experience of the two-joint robot arm, HIT and DLR has jointly developed a reconfigurable modular robot in 2005, which was composed of six same modular joints and a gripper. This robot overcomes the above disadvantages and was developed for a free-flying robot project [6]. The robot can't support its mass all by itself, should be working in a zero gravity environment.

In the last two years, HIT-DLR lab has developed a new generation of multisensory flexible joint robot: HIT-DLR robot. A full state measurement and feedback system (motor position, link position, and joint torque) were embedded into HIT-DLR robot. The goal of the project is to realize a system which was fully built up on all the experiences made with the former robots, and designed toward higher force to sustain itself work on the ground without assistant suspending system.

This paper will be arranged as: Section 2 gives an overview of the HIT-DLR robot; Section 3 describes the multisensory system of the robot arm; Section 4 and 5 present the hardware and software architecture respectively; Conclusion is addressed in Section 6.

II. OVERVIEW OF THE HIT-DLR ROBOT

The HIT-DLR robot is made up of a multi-sensory integrated four-joint robot arm and a DLR-HIT-Hand, as shown in Fig.1. In order to achieve a high degree of modularity, all four joints are identical in the macro structure. The joint is powered by electro-mechanical drives, consisting of brushless DC motor in series with light harmonic drive used for speed reduction. In order to save space, the system is designed foldable. Configuration of the manipulator is rotation-pitch-pitch-pitch. The HIT-DLR robot is 1.3m overall length and 25kg weight. There are only 6 cables through the robot, including 2 cables for power supply and 4 cables for serial communication bus.

Fig.1 The HIT-DLR robot

The joint is consisted of a brushless DC-motor, motor position sensor, joint link position sensor, power-off safety brake, harmonic drive gear, torque sensor and control electrocircuit. To realize highly integrated mechatronic design, all these components are placed inside the housing to be as space-saving as possible, as shown in Fig. 2. Avoiding the cables twist in the robot, the joint is designed with a hollow shaft to allow central cable passing. This demands all the relevant joint components having big center hole. The motors of 1.4Nm and 0.46Nm torque are selected, with reduction ratio 160:1 harmonic drive, to supply 4 joints need. A permanent

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magnet brake is proximately close up the motor, which is automatically engaged in case of power failures. Next to the safety brake, the electronics boards are placed to supply the joint sensor data processing and control. Abundant sensors are integrated in the joint inside, which will get specification in the next chapter.

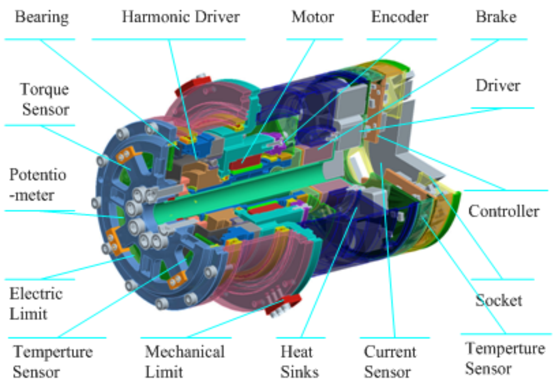

Fig.2 Structure of modular joint

The multi-finger dexterous hand of HIT-DLR Hand has been chosen as the end effector. The dexterous hand with total thirteen DOFs (Degree of Freedom) has four fingers and a palm. Each finger has three DOFs and four joints, last two joints are mechanically coupled. The thumb has an additional DOF to realize the motion relative to the palm. The high degree of integration and low weight (1.5kg) make the HIT-DLR Hand can be mounted on a manipulator. It has been proven that the dexterous hand can accomplish various complex tasks such as playing piano and pouring water from a bottle into a cup, and can fit for the system’s design demand. The HIT-DLR Hand is shown in Fig. 1, its structure and control architecture have been described in reference [7].

III. MULTI-SENSORY SYSTEM OF THE ROBOT ARM

A dexterous robot arm at least needs a set of force and position sensors to enable control schemes work as position control and impedance control in autonomous operation and tele-operation. So, multiple sensors are well equipped in each joint, as shown in Table Ⅰ.

TABLE I
SENSORS IN ONE MODULAR JOINT

Number	Name	Quantity	Principle
1	torque sensor	1	strain gauge
2	link position sensor	1	potentiometer
3	limit position switch	2	hall effect
4	Magnetic encoder	1	hall effect
5	motor position sensor	3	hall effect
6	temperature sensor	3	thermometer
7	current sensor	2	hall effect

The joint link angular sensor is a key component for joint position control. A potentiometer and a magnetic encoder are equipped to measure the absolute angular position of the joint and the motor respectively. As a motor position sensor, a low weight and low inertia magnetic encoder has been employed; as output position sensor, a potentiometer has been designed. Syncretize the two sensor data, the robot could provide accurate shaft position information to implement precise position and velocity control. The utilization of the Hall linear sensors would also allow for the motor shaft position information to support both commutation and position control.

The joint torque sensor was designed based on shear strain theory. Eight strain gauges were used to construct two full-bridges, which could compensate the effects of temperature and transverse forces. The Sub-problem Approximation method of Ansys software was introduced to optimize the structure of the torque sensor. During the optimization process, several relevant geometric dimensions are utilized as design variables, strain and stress are state variables and weight is the object function. The weight of the torque sensor has been reduced 16% compared with the initial design.

IV. HARDWARE ARCHITECTURE

The control structures of HIT-DLR robot have been mainly developed based on FPGA/DSP. Fig. 3 gives an overview of the hardware and software architecture of the whole control system. In order to minimize cabling and weight of the HIT-DLR robot, a fully mechatronic design philosophy is introduced to develop the hardware system. The hardware system consists of PCI-based DSP/FPA board which configured as a Master, joint FPGA board and hand FPGA boards which configured as Slaves. The Master board performed as a Cartesian level, calculate robot kinematics, dynamic compensation and other computations such as trajectory generation etc., which can be carried out in the DSP more efficiently. The Slave boards are responsible for the interface functions with the real world, such as PWM signal generation, interface to ADC, etc. Communications between the Master and Slave via two data buses at a speed of up to 25Mbps, which are PPSeCo used for the hand [8] and M-LVDS Serial Data Bus used for the 4-DOF arm.

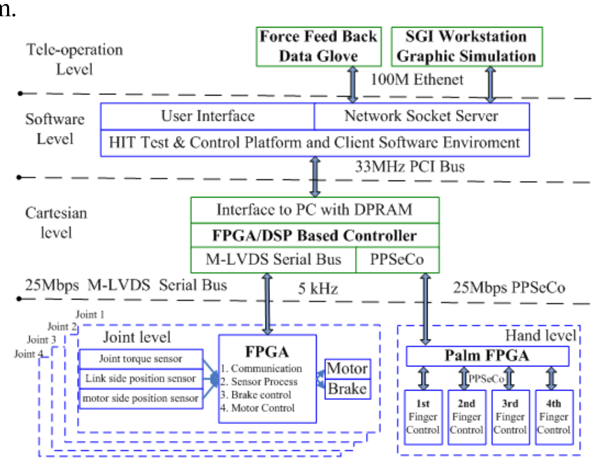

Fig.3 Controller architecture

A. M-LVDS Serial Data Bus

To implement the real time feed back control of the multisensory arm, a large amount of data need to be transmitted between the DSP and the hardware. The data consists of 4-th order joint state (motor position, joint torque, and their derivatives [9]) and the motor control data. Because of the large amount of data, the communication between the FPGA and the DSP needs to be quite fast. One probable interface is Universal Serial Bus (USB), which today is a standard interface in PC. The USB interface is very fast, up to 12 Mbps, but is not suitable for our systems that require low-power, low noise and high immunity [10]. Another fast interface is FIRE-WIRE(IEEE-1394), whose bandwidths is over 1Gbps. However, FIRE-WIRE is not yet common in regular computers and very complex to implement in FPGA. Parallel communication is another interface, which is quite fast, easy to implement and uses only a small part in the FPGA, but it needs many cables.

Multipoint Low Voltage Differential Signaling (M-LVDS) allows multipoint configurations of LVDS and is defined by the ANSI/TIA/EIA-899 M-LVDS Standard which recommends a maximum data rate of 500Mbps. In order to increase the transmission speed and reliability of data communication, reduce cabling and noise in sensor signals, an M-LVDS Serial Bus system was designed for the data communication (half-duplex) between the arm and DSP/FPGA board. In order to realize these requirements, M-LVDS Serial Bus should have the following characteristics.

--M-LVDS Serial Bus uses a 16-bit cyclical redundancy check (CRC) checksum based on the CCITT polynomial $x^{16} + x^{12} + x^5 + 1$ (The same function used by the modem protocol)to ensure the majority of communication errors can be detected.

--NRZI data encoding and automatic bit stuffing/stripping are used for data encoding.

--Variable baud rate (typically with a bandwidth of 25 Mbps and cycle time less than 200 us was achieved).

The slim, package-based protocol (M-LVDS Serial Bus) has been implemented in PCI board and all joints. All communication and other control program for all FPGAs are written in VHDL and run in FPGAs. With this communication technology, the PCI-DSP can concentrate on calculating some more complex algorithm.

B. DSP/FPGA PCI board

The main controller of the DLR-HIT-Hand is a TI floating-point digital signal processor (DSP) TMS320C6713 [11] with maximum 1350 MFLOPS. Some characteristics of this board are as follows: 225 MHz clock, floating point arithmetic unit, 32Mbyte SDRAM, 512 K bytes flash program memory and 16 K dual-ported RAM. It's a high performance embedded processor system that is able to operate standalone as well as a slave component. According to the high performance and unique hardware structure of the DSP, it's an optimal alternative to realize complex control algorithm and very fast computation easily, thus the board is an excellent choice for multi-channel communication and multi-function application. Further more, the DSP board provides a series of peripherals which make it easy for designer to access and extend the hardware resources.

Based on the DSP, a PCI-based DSP/FPGA board was designed (as shown in Fig. 4). The PCI board exchanges data with PC via PCI bridge controller. At the same time, the board communicates with the hand via PPSeCo and communicates with the arm via M-LVDS Serial Bus through the Port 1 and Port 2, achieved absolutely by the way of hardware. DSP and FPGA achieve data exchange via a fast parallel interface on the PCI board. All high level data processing is implemented on the DSP board. DSP mainly plays as a computing unit for complex control algorithm because of its high performance floating-point capabilities. And the FPGA communicates with external components from the PCI board via serial interface. The FPGA converts serial signals from the slave FPGAs to parallel signals and transmits them to the DSP via the parallel interface, and vice versa.

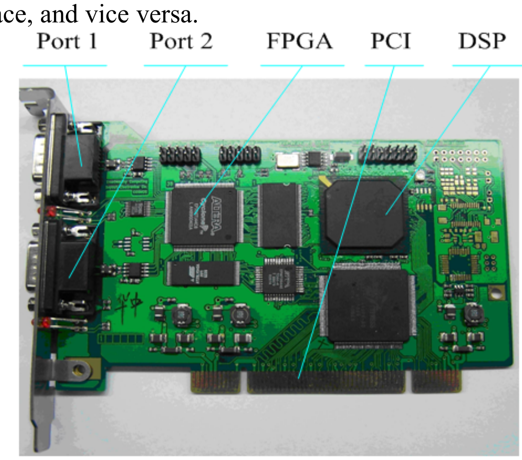

Fig.4 DSP/FPGA PCI board

C. Joint electronics

One major goal of the arm design is a fully integrate all necessary electronics and actuators in each joint. So, the joint electronics is integrated in the joint, by means of five circular boards (Sensor board, magnetic encoder board, Drive board, Control board, Socket board), interconnected with micro multi-way socket and flex cables, and is schematically shown in Fig. 5. The five boards are respectively in charge of the following main functions.

--Sample the torque and joint position sensors.

--Get the motor position.

--Generation of auxiliary voltages from 28V power bus, Motor and brake driver, motor and brake current acquisition.

--M-LVDS bus interface and FPGA-based joint control, in charge of the sensory data collection and the control of the joint.

--Data bus and 28V power socket, in order to easily knocked-down.

Each joint's electronics is a node on the HIT-DLR robot power and data bus (M-LVDS serial bus). This distributed architecture with the electronics incorporated into the joints, ultimately reduce the number of multi-wire cable harnesses, thereby saving system mass and increasing system reliability, improving robustness with respect to EMC, having joint electronics located close to the sensors and the actuators, and still providing the needed data exchange frequency, satisfying control system bandwidth requirement.

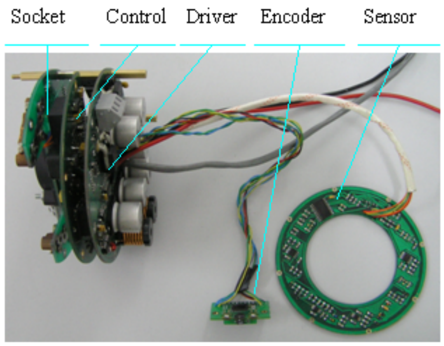

Fig.5 Overview of joint electronics

V. CONTROL ARCHITECTURE

Based on the hardware architecture of the HIT-DLR robot arm, the software architecture has been developed according to the principle of multi-level structure and modularity. As shown in Fig. 3, all data processing and control algorithm of the arm are realized in four levels. In Joint level, sensor data acquisition and motor actuation are implemented by joint FPGA. The Cartesian level implements all computation for the arm and provides basic client interface for PC software level. PC software level serves as a monitor level, displaying the robot state in time and interface for Tele-operation level to get external commands. Control algorithm, Joint level and Cartesian level will be introduced in detail as following.

A. Control algorithm

The control structures for this arm have been mainly developed, referring to Fig. 6. The model of HIT_DLR robot could be demonstrated as followed expressions:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau + \tau_{ext} \qquad (1)$$

$$B\ddot{\theta} + \tau = \tau_m \qquad (2)$$

In the equation, $M(q)$ represents the inertia matrix, $C(q,\dot{q})\dot{q}$, the centrifugal and Coriolis terms, and $g(q)$, the gravity torques of the link side rigid body model. In order to take account of the coupled joints the generalized motor position θ are introduced which are related to the physical motor angles θ_{phys} via a constant matrix T in the form $\theta = T\theta_{phys}$. The vector of the joint torques is given by $\tau = K(\theta - q)$, whereby q indicates the vector of the link side joint angles, and K, the diagonal joint stiffness matrix. In addition, τ_{ext} is the external torques and τ_m is the generalized motor torque those are regarded as input variables for the controller design.

With regard to the presented application, Cartesian impedance control is particularly of interest. The goal is a defined impedance behavior between external (generalized) forces acting on the robot and the end-effector movement. At the same time, a simple PD control plus on-line gravity compensation in the joint space can be adopted to realize high-precise trajectory tracking [12, 13]. So, in order to apply the optimal control to different targets, impedance control and PD with gravity compensation control are considered.

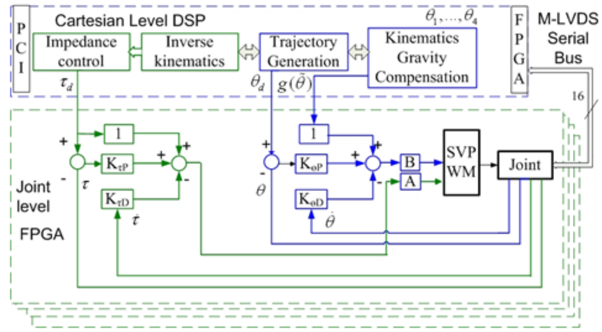

Fig.6 Diagram of the Master/Slave control architecture

B. Joint level

In the joint level, the FPGA-based motion control IC to be designed will be used as a programmable ASIC. The functions include A/D converter, velocity estimator, current sensing, SVPWM control, brake/fault and so on.

The Cartesian control from [9], [13] is designed according to a cascaded control structure. An inner controller is introduced as:

$$u = A*(\tau_d + K_{\tau P}(\tau_d - \tau) - K_{\tau D}\dot{\tau}) + B*(K_{\theta P}(\theta_d - \theta) - K_{\theta D}\dot{\theta} + g(\tilde{\theta})) \qquad (3)$$

Where, $K_{\tau P}$, $K_{\tau D}$, $K_{\theta P}$ and $K_{\theta D}$ are all constant positive definite symmetric (and typically diagonal) matrices which get by experimentation. With A =1, B =0 obtains its desired torque τ_d from an outer impedance controller as a form of an inner torque controller. With A =0, B =1 obtains its desired position θ_d from an outer gravity compensation as a form of an inner position controller. $g(\tilde{\theta})$ is the gravity compensation, which will be calculated in the Cartesian level.

C. Cartesian level

The HIT-DLR robot model parameters (joint mass, center of gravity, length of robot link) are directly generated from the mechanical CAD design. So the gravity compensation can be obtained on line with a new introduced variable named "gravity-biased" motor position.

$$\tilde{\theta} = \theta - K^{-1} g(q_d) \quad (4)$$

According to the impedance control law and the torque control law (3), an outer controller is constructed to achieve the desired impedance behavior.

$$\tau_d = g(\tilde{\theta}) - J(\theta)^T (K_d(x(\theta) - x_d) + D_d \dot{x}(\theta)) \quad (5)$$

The desired impedance can be specified by a stiffness matrix K_d and a damping matrix D_d. These matrices are defined by a set of suitable Cartesian coordinates $x(\theta)$ which determine the posture of the end-effector. The corresponding Jacobian matrix is indicated with $J(\theta) = \partial x(\theta)/\partial(\theta)$. The desired virtual equilibrium position is given by trajectory generation x_d. It must be noted that the equilibrium condition $\tau = K(\theta - q) = g(q)$ must be fulfilled, when the robot does not touch any environment.

In the position control law, The DSP should get joint desired position θ_d by Cartesian trajectory generation and inverse kinematics,

$$\theta_d = J(\theta)^T x_d \quad (6)$$

At the same time, the gravity compensation $g(\tilde{\theta})$ should send to each joint in time by M-LVDS serial bus.

VI. EXPERIMENTS

In the first experiment, a single joint is used to demonstrate the impedance characteristics (K_d=1000, D_d=10) while using Cartesian impedance control architecture. As the Fig.7 shows, the joint tracks the sine position trajectory (dashed line) and contacts a rigid environment below the joint angle 1.85°. Real tracking curve is shown as the solid line. Corresponding to the trajectory tracking of Fig.7, the poison tracking error (dashed line) and joint torque (solid line) is shown in the Fig.8. The results of this experiment show: the joint can follow the desired trajectory ideally within the free space. The joint torque will increase equably while it contacts the environment.

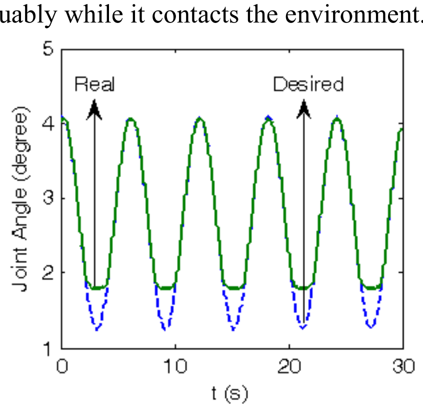

Fig. 7 Position tracking with environment contract using impedance control

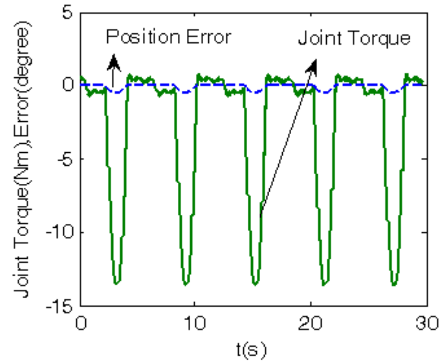

Fig. 8 The tracking error and joint torque

Cartesian impedance characteristics in the HIT-DLR robot are also demonstrated. At first, the robot pauses at an virtual equilibrium pose C_D=[0,0,0,0,0,0]. For the desired stiffness and damping matrices, diagonal matrices from table II are used. The robot was pulled in different directions showed in Fig.9. Finally, the robot will overcome the gravity and return to the C_D as soon as we release the force. Fig.9 shows the corresponding Cartesian forces along with the Cartesian position. It can be concluded that the ideal Cartesian impedance behavior is successfully achieved as theoretically predicted.

TABLE II
IMPEDANCE PARAMETERS IN WORKSPACE

Cartesian coordinates	X	Y	Z
Stiffness (N/m)	5000	5000	550
Damping (Ns/m)	782.6	782.6	78.3

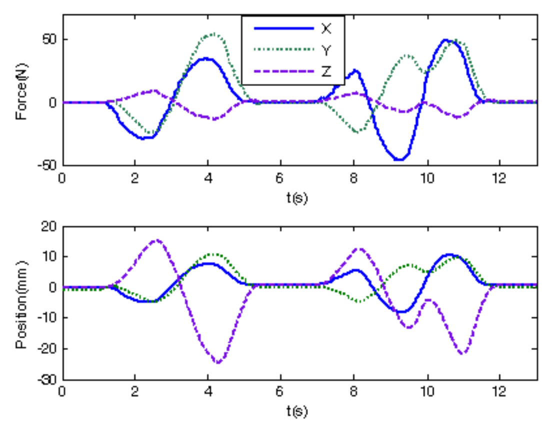

Fig. 9 Cartesian coordinate varies in Cartesian impedance control

VII. CONCLUSIONS

The paper presented a hardware and software architecture for the HIT-DLR robot. Multi-sensors had been implemented in the module joint, which could monitor the joint torque, motor and link positions, motor phase current and so on. A new DSP/FPGA-based master/slaver system had been designed to implement the motion and impedance control. In the joint level, the joint motion controller with sensors processing was verified and implemented on one-chip FPGA. PCI-based DSP/FPGA board had been designed to realize the Cartesian level control.

M-LVDS serial data bus was designed with 200us cycle time to communicate between Cartesian level and joint level by the using of the FPGA. Cartesian impedance control has been successfully implemented in this hardware architecture. Furthermore, the experimental results demonstrated its feasibility of giving satisfactory tracking performance and Cartesian impedance performance in the HIT-DLR robot.

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