Advanced DC Motor Drive for Haptic Devices

Miroslav Božić, Darko Todorović, Miloš Petković, Volker Zerbe, and Goran S. Đorđević

***Abstract*—Haptics covers many different forms of mechanical interaction with human senses by engaging, touch, vibrations and forces/torques, established for the purpose of augmenting the feedback structure during human-machine interaction. A haptic device has mechanical part, moved by actuators from one and human hand or fingers from the other, actuators, drives, sensing elements, as well as algorithms designed to control the interaction between human and machine in positioning and motion control tasks. With such a system, motors can be controlled in a way to simulate various environments, defined by their material and dynamics, for example pushing soft ball uphill. Haptic devices are becoming more popular in medical applications after introduction of modern medical robots with many different extensions for minimally invasive surgery or diagnostics based on palpation. This paper discusses one DC motor driver custom designed for the purpose of designing a haptic device for medical applications.**

***Index Terms*—Haptics, DC motor drive.**

I. Introduction

STEPPING out of industry was a challenging task for robotics scientists and engineer. Even now, after more than 25 years after establishing a first medical robot application where PUMA560 robot was placing a needle for brain biopsy using CT guidance, still we have no autonomous robot ready for any medical intervention. In reality, we are witnessing very effective robot installations reaching the level of restrained medical assistants, reliably and passively replicating or augmenting human manual commands presented at the handles, joysticks or specially designed mechatronic interfaces. The most prominent is Intuitive Surgical's da Vinci Surgical System. Simple but effective explanation is that living organisms are so complex in their structure and emerging forms, being healthy tissue or not, it requires another living organism with abundance of sensorimotor skills to perform even the simplest surgical intervention. From engineering point of view, it can be said we can have programmed elemental interaction but we cannot have a complete program that will engage the skills in reliable manner of timing, sequencing or scaling. For that, we still need a surgeon that has all theoretical and practical knowledge while the robot will be only its extension to-wards better precision in positioning and applying force, less tremor, leading to successful and less invasive surgery. However, the most important achievement of robotic surgery is that it might help less trained surgeon to perform a standard surgery in a more reliable way but its overall success is limited within a scope of human skills. There is no surgery or diagnostics that robot can do while human can-not. Even worse for robotics, statistical evaluation of robotic-assisted surgery (RAS) vs. manual surgery shows no obvious benefit to patient's health, as RAS takes longer, it requires skills available only to additionally trained surgeons located at top-notch hospitals, and robotic surgery systems are still not developed enough at the point where human get hands on the robot. The weakest point of today's surgical robot technology is its human-machine interface part as the variety of interactions at that port is huge and so complex no modern technology tools and algorithms can provide its dependability.

The work presented in this paper aims the technology that will enable better HMI based on mechatronic system often called joystick, actuated with high performance DC motors. We developed Advanced Motor Drive for Haptic Devices (AMD–HD) with plenty of interfaces, functions, and processor support that can handle even motor skills of humans based on data after extensive exercising. The drive can be coupled with the other drives towards programmable bilateral interaction thus leaving a global control effort for the upper level where the strategy of interaction is considered. This paper describes the drive, its structure and purpose, accompanying software for drive programming to meet requirements needed for truly versatile haptic device.

II. AMD–HD Drive Description

The AMD–HD motor driver is designed to meet requirements such as precision, dynamics, reliability, connectivity, and scalability of high performance DC motors such as Maxon's RE series motors are. It supersedes generic Maxon drives well known as expensive and not so reliable drives. Among other, more expensive and reliable drives on the market, we did not find any driver that will naturally suit the needs in haptic devices for fast model-based control between the drive interactions due to the need of mechanical cross coupling required for achieving desired mechanical impedance projected at human hand in the whole workspace.

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The AMD–HD is based on micro-controller system that handles all: velocity and torque estimation, speed and torque control, position control, and even model-based control. Dedicated PC software handles GUI. The Driver and GUI software communicate via RS232/485 serial bus thus enabling multiple drive control within the same supervisory application at PC side.

A. *Drive properties*

The Drive nominal operating voltage is between 20 VDC and 90 VDC. Maximum output voltage is 72 VDC. Maxi-mum output current 15 A (for less than 30 sec). Continuous output current is 10 A. Pulse Width Modulation frequency is 40 kHz. While the sampling rate is programmable and can be as low as 10 kHz, maximum motor speed is limited by maximum permissible speed (motor) and max. output voltage (controller). The dimensions of the drive are WxLxH: 148x148x40mm. Total weight with cooler is approx. 150grams.

Photo of the AMD–HD driver is shown on Fig. 1, with main modules numbered as:

1. Power Supply Unit
2. Control Unit
3. Motion Feedback Module
4. Analog-Digital IO module
5. Communication module
6. Motor current sensing module
7. H-bridge

The Drive has dedicated Power Supply Unit, with standard +5V, +12V, +V DC voltages for H-bridge. Noise is reduced by DC-DC converter with +V at input. Additional stabilization of voltage at the converter output supplies control circuitry. Microchip's PIC18F4431, besides its standard peripherals, has 4 independent complementary 14bit PWM modules; motion feedback module for data logging from quadrature signals of incremental optical encoder, 200 ksps 10bit AD converter; all making it almost perfect for the task we are targeting. Both,

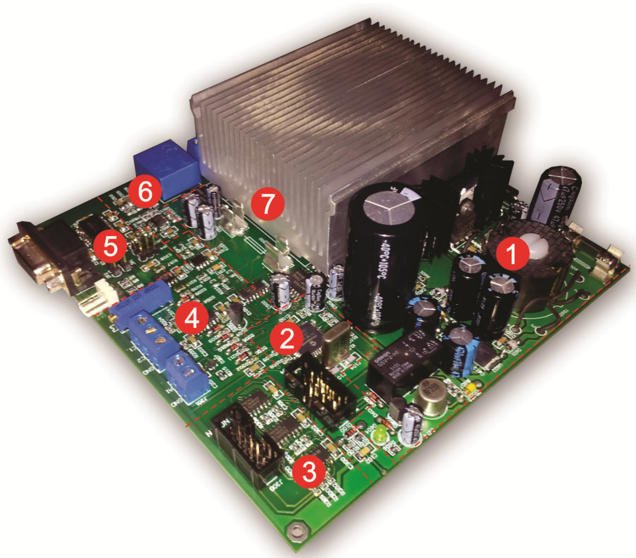

Fig. 1. AMD-HD DC motor drive.

TTL and Differential inputs from encoders are handled by using 26LS32 line driver and 74HC157 Quad 2-Input Multiplexer as data selector. Encoder selection is possible within GUI software. Additional analog input 0 to 5VDC is available for position or velocity commands. Finally, two digital open collector inputs DI1 and DI2 are available for drive configuration from the GUI. The Drive communicates with GUI at PC level via RS232 point to point and RS485 multi point serial communication.

B. *Current sensing*

Current measurement is one of the most important pro-perties of the Drive, as required for mechatronic technologies such as haptics. Precise current sensing can be related to the interaction force exerted between mechanics (linked to the motor) and human hand. For that to happen, it is crucial that mechanics efficiency of all transmissions (primarily, from gearbox, and secondary) is as low as possible and considerable amount of human machine interaction is feed back to the motor shaft for further estimation of cur-rent. The nature of such interaction points out sensitivity over bandwidth as hand movements are more soft and slow than strong and fast. Having that in mind we choose LEM HXS10-NP current sensing element. Sensor output is fed into non-inverting CMOS Op-Amp MCP601. The gain is set so that 1VDC corresponds to motor current of 1A. By setting up resistance the maximum gain is 2.5VDC/10A. The amplified signal is brought to analog input of micro–controller. The digital signal of current sensed is sent to GUI at PC.

Having in mind that output voltage of LEM sensor is:

$$V_{LEM} = V_{REF} \pm \frac{0.625 \cdot l_M}{l_{MAX}},$$

and the gain of amplifier is:

$$G = 1 + \frac{R_3}{R_2},$$

then, the voltage at the microcontroller input is

$$V_{MCU} = V_{REF} \pm \frac{0.625 \cdot l_M}{l_{MAX}} \cdot G.$$

C. *GUI software*

Dedicated GUI software, MCA-1 Monitor, handles all drive settings, PC peripheral configuration, data recording and visualization. Its main widow is shown in Fig. 2.

This application handles:

1. COM port selection on PC where the driver is connected,
2. Address selection to be used by driver, for read and write of new parameters,
3. Free address assignment to non-configured driver
4. Inspection of Drive parameters such as: type, driver supply voltage, motor nominal voltage, maximal pulses of incremental optical encoder, encoder output signal type, motor brake operating voltage, gearbox ratio, digital input function selection.

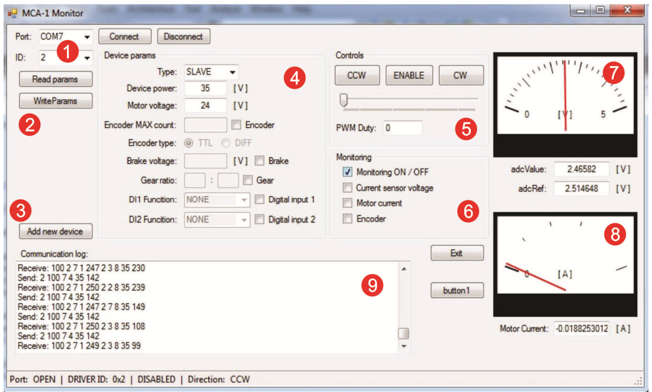

Fig. 2. Main window of MCA-1 monitor GUI

5. PWM duty cycle selection along with direction of rotation.
6. Motor parameter inspection
7. Current sensor voltage
8. Motor current sensing
9. Communication log.

This application also enables current data logging and grahipical visualization in time-based diagrams, as shown in Fig. 3.

Arbitrary interaction with gearbox shaft with fingers produces the torques sensed and recorded by the driver. From Fig. 4, it is obvious that calculated motor current, shown with blue line, compared to LEM current sensor output, shown with red line, has very similar dynamics, almost without phase shift, and gain increase of approximately 82. The phase shift and filtering properties of the two signals should be correlated for further elaboration.

D. *Communication Protocol*

With rapid development of embedded systems, and significant price and development time reduction, distributed data gathering and local processing, based on reusable modules is becoming the mainstream model for rapid prototyping and final product development. In order to fulfill all the needs in matters of bandwidth, reliability and information security, appropriate protocol for communication between DC motor driver and PC, as well as between drivers themselves was defined, and communication libraries for .Net and microcontroller were developed.

The AMD–HD driver communicates with PC GUI software

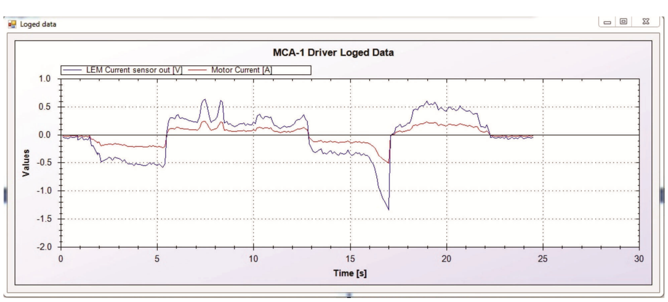

Fig. 3. Recorded voltage signal (at LEM sensor output) and calculated motor current.

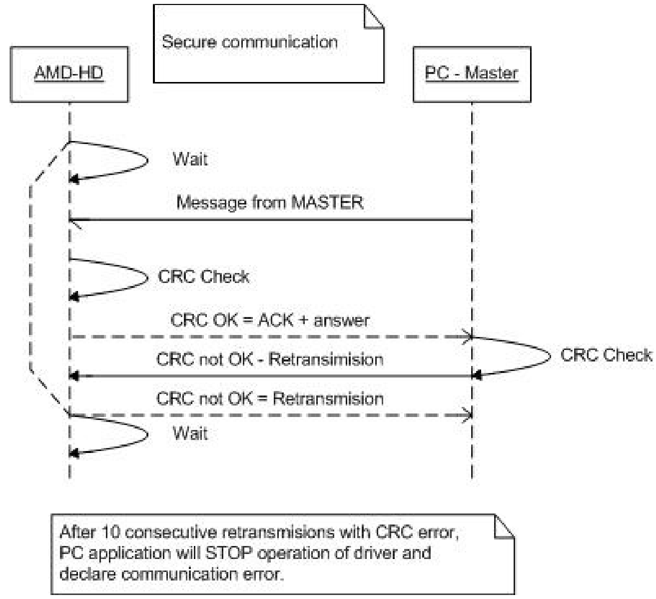

Fig. 4. Secure communication timing diagram.

via RS232 PTP or RS485 MP connection. Jumpers on the board are used for type selection. Also, two drives can be attached via I2C bus, but only the Master of the two drives can be controlled while the Slave will follow the Master. Message exchange protocol is explained with the timing diagram given in Fig. 4.

At first, we defined the time diagrams that describe the flow of messages and rules of communication between devices on global level shown on Fig. 4. Here we can see two timelines; first timeline is associated with AMD-HD (DC motor driver) and second is associated with PC which acts like a master device in communication. Because we use RS485 serial communication protocol on physical layer, we must have at least one master node at a time. As you can see on figure xx, the CRC is added at the end of each message and checked on each side. If CRC is not equal with calculated one, then the message retransmission is requested from both sides. In some modes, like PC monitoring, retransmission is not requested because the new driver state will be sent in next message again. The message with error will not be considered in that case. If 10 messages in a row come with errors then there is a communication failure and communication is stopped, to be sure not to make some damage.

Every message has defined structure and meaning. The structure of message is determined by the MUN (Message Unique Number) field. Based on this field, recipient can determine type of message, length and order of useful bytes. On Fig. 5 the structure of each message is shown.

Byte 0	Byte 1	Byte 2	Byte 2+n	Byte 2+n+1	Byte 2+n+2	Byte 2+n+3
ADR_ REC	ADR_ SEND	MUN	DATA_ BYTES	NBR	#	CRC

Fig. 5. Message format.

First and second byte, define addresses of receiver and sender respectively. Third byte is already mentioned MUN byte, after which useful, data containing bytes are defined represented with DATA_BYTES. After useful data bytes, message length byte is placed and used for decoding purposes, after which termination byte represented with "#" character. At the end of the message calculated CRC is placed. Decoding on receivers side starts with finding the termination character and comparison between counted and the length of message in NBR byte. At the end CRC is checked and message is declared good or with errors.

E. Simulation

Modeling of H-bridge motor driver is considered trivial as extensive research was published in the last decades such as [1], and [2]. Modeling of Maxon DC Motors in Simulink is already done as well, and one of better models is found in [3] as a freeware. We have used that motor mo-del but with catalogue data for Maxon motor RE40 [4, 5] as parameters. From practical point of view these simulations are not needed in haptic devices. Instead, for safety reasons we do need state transition diagrams of the drive for safe interaction with human operator. This should also include the safety system tailored for such purposes.

III. Experimental Setup

This study and development has been undertaken for projects related to medical applications where human-machine interface is needed through controllable bilateral mechanical interaction. We chose high performance Maxon DC motor RE40, code 263075, operating on 48VDC, with 987 rpm no load speed, maximum continuous torque of 0.19Nm and torque constant of 461mNm/A, [4]. Such a motor is recognized among the others of the same family as the best transformer of output torque into motor current. Its low speed also makes it very suitable to be used in haptic interfaces. Even alone motor has enough torque to produce sensible force/torque on a standard mechanical device such as joystick. Here we added a high efficient planetary gearbox from the same manufacturer with 4.3:1 gear ratio and 9.4gcm2 mass inertia [5]. Such a gearbox is very compliant backwards, meaning that motor can sense the torque applied on the gearbox shaft without considerable loss of information. The motor is also equipped with standard incremental optical encoder HEDS series with 500ppr. AMD-HD motor drive along with gear-motor-sensor application is shown in Fig. 6.

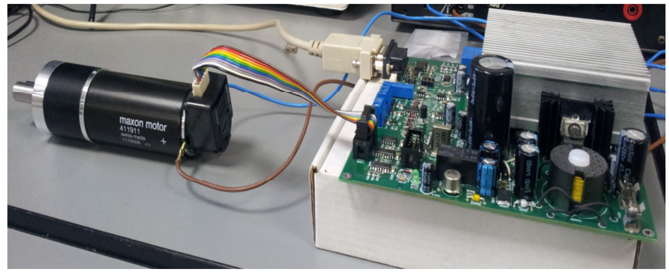

Fig. 6. Drive (to the left) and geared motor RE40.

IV. Conclusion

Advanced drive for DC motors is designed with focus on driving haptic devices with such system. It has several advantages as compared to the drives met on the market. First, it has high sensitive current sensor LEM HXS10-NP included meaning we can measure the interaction with environment (even through a gearbox of modest ratio) by measuring the current. Also, it can operate simultaneously with other drives, exchanging data on current, velocity, position and actual state of the motor. This makes it very useful in integrating it into a hierarchical control system where upper level of control is done at embedded controller while the motion itself along with interaction is left to be handled at the driver side. This is particularly useful in haptic devices where the interaction is complex dynamics and it requires special calculations. Finally, on-board processor can be used for customized model-based control (analytic or data-based) thus making this drive a perfect companion of the motor in the given mechatronic system.

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