Intelligent Excavator for Hydraulic Mobile Machine

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***Abstract*—Attachments and their controls can be connected to hydraulic mobile machines in different ways. The traditional approach is to install hydraulic valves of the attachment close to the operator. Thereby levers of the valves can be reached from the operator seat. This, however, restricts the size and number of the valves and can be inconvenient for the operator. A more advanced and ergonomic way is to use electronic control which allows installing the valves more freely on the attachment. The operator can then control the attachment with a joystick, for example. Usually there is a microcontroller unit in an electronically controlled mobile machine. One solution is to use this unit to read the joysticks and output control signals to the valves of the attachment. However, if there is a microcontroller in the attachment as well, the wiring can be minimized and the attachment can perform intelligent functions, for example positioning, as the machine sends simple commands. The data transfer between the microcontrollers can be realized flexibly and reliably using a serial bus such as CAN.**

A hydraulically operated excavator for a hydraulic mobile machine is discussed as an example. The excavator has four PWM controlled spools in a sandwich type proportional mobile valve. A suitable microcontroller is chosen to interface the valves of the excavator to the CAN bus of the mobile machine. Different command sets and levels of intelligence are deliberated. Adding different types of sensors to the excavator is concerned. The sensors are used to achieve more accurate, independent and safe operation. The microcontroller unit is designed to have extra interfaces for future research with different sensors. The unit is designed, built and installed to the excavator. The design of electronics and software is presented in this paper. The excavator is attached to the hydraulically operated mobile machine and the performance of the system is tested. The test arrangement is described. The results are presented and discussed.

***Index Terms*—CAN, intelligence, mobile machine, proportional valve.**

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I. INTRODUCTION

MOST hydraulic mobile machines are multipurpose instruments. They have different attachments for different functions. In many applications the changing between these attachments should be as easy and quick as possible. Furthermore, attachments may have several hydraulic cylinders, motors and valves. Connecting these complex attachments to the control system of a mobile machine can be a problem.

In this paper a skid steered hydraulic mobile machine with a back hoe excavator attachment is discussed as an example. The basic machine is made by Avant Tecno and modified by Institute of Hydraulics and Automation at Tampere University of Technology.

A. Mobile machine

The commercially available model of the machine is Avant 320+. It has no electronic control system and all the valves are mechanically operated [1]. In previous research an electronic control system with CAN (Controller Area Network) and wireless teleoperation has been developed for the mobile machine [2]. A photograph of the modified machine is in Fig. 1. Visible parts of the electronic control system in the photograph are the electronic joystick and the display module. Also the steering wheel and accelerator pedal have electronic sensors. The sensors and valves are connected to two MVMIO24 I/O modules that communicate with the MVDM586 display module via CAN using CANopen protocol. The modules are commercial products from Axiomatic Technologies [3], [4]. Battery voltage and CAN are wired to a four-pole connector behind the bucket. If the attachment communicates via CAN, there is no need for other electrical connectors.

In this work the only changes to the mobile machine are small software modifications. No extra joysticks will be installed because one of the objectives is that there is no need for attachment-specific input devices.

Fig. 1. The modified Avant 320+ mobile machine with electronic control system.

B. Back Hoe Excavator

The excavator has four cylinders. A photograph of the attachment is shown in Fig. 2. One cylinder turns the first boom segment laterally and the others raise and lower the other two boom segments and the bucket.

In the commercial version, Avant Backhoe 205, each cylinder has a mechanically operated valve. The valves have been replaced with a sandwich type proportional mobile valve with six PWM (Pulse Width Modulation) controlled spools for experimenting with electronic control. The valve is PVG 32 from Sauer Danfoss [5]. Two of the spools are not used. In this paper the main focus is on the design of interface electronics and software for the excavator.

There are, of course, commercial enclosed microcontroller units that could be used, but they are not so flexible. Available selection of different performance categories is limited. The software development is often restricted compared to a separate microcontroller circuit. The dimensions of the case may be too big for some attachments and suitable connector options may be difficult to find.

Fig. 2. The Avant Backhoe 205 excavator with PVG 32 valve.

II. Design Criteria

Attaching the excavator to the mobile machine should be as easy as possible. Mechanical and hydraulic connections employ quick couplings already in the commercial versions. Using a single four-pole connector for power and CAN enables easy electrical connections. Therefore interface electronics should include a CAN transceiver. CAN also makes it possible to transfer configuration data and high-level commands in addition to ordinary control data.

It should be possible to operate the excavator from the operator seat and teleoperation unit without any extra input devices. This is because adding an attachment should not require notable modifications to the mobile machine. The joystick and the steering wheel are not needed by the mobile machine when the excavator is operated. Therefore, they can be used to operate the excavator.

Most proportional mobile valves are PWM or voltage level controlled. In this case PWM outputs are sufficient. Future research includes different sensor types, e.g. pressure and position sensors. This requires analog inputs. Voltage inputs would be desirable because also current signals are easy to convert to voltage. Some digital general purpose inputs and outputs are needed for different types of smart sensors.

The interface module should have a flexible microcontroller that has enough performance and program memory to handle the sensors and run demanding control algorithms. Some non-volatile memory is also needed to store parameter data.

The only reasonable source of electric power is the battery of the mobile machine. Therefore the electronics of the excavator should have moderate power consumption.

The mobile machine is designed to operate outdoors. The electronic components should tolerate the temperature range from -40°C to +80°C. The module should also be protected against dust and humidity.

There is a lot of space for the electronics in the excavator thus the size of the interface module is not critical. Many attachments, however, have limited space. On that account, a general purpose interface module that fits in a small case would be useful for future research.

III. Electronics

Because different attachments have different requirements for the control unit, a modular approach was chosen. First, a small multipurpose microcontroller board was designed and produced. The idea is that the same microcontroller board can be used to control any attachment. Then, an attachment-specific board with a voltage regulator, a driver circuit, and wire connectors was built to be a motherboard under the microcontroller board. A dust and water proof metal case and cable glands were selected. The two boards were connected and enclosed in the case.

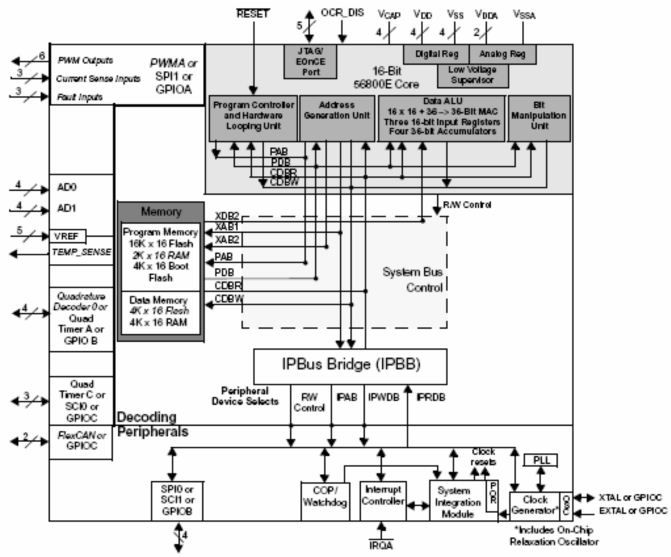

Fig. 3. Block diagram of the 56F8323 microcontroller.

A. Microcontroller Board

To reduce the size and cost of the system, a microcontroller that had the most desired functions integrated was chosen. In this case it was 56F8323, a 16-bit hybrid microcontroller from Freescale Semiconductor. The block diagram of the microcontroller is shown in Fig. 3. It has six PWM outputs which is sufficient for most attachments. Three of them have optional current feedback inputs for current controlled devices. There are three fault inputs that can be programmed to disable desired PWM outputs. For analog sensors there are 8 analog inputs with a resolution of 12 bits. [6]

The microcontroller has a CAN 2.0 B-compliant FlexCAN module that enables CAN communications with any high-level protocol such as CANopen, DeviceNet, or SAE J1939. There are two asynchronous serial ports. One of them, or the PWM outputs, can be configured to be a synchronous SPI (Serial Peripheral Interface) that enables connections to smart temperature sensors, for example. The microcontroller also has a quadrature decoder for one incremental sensor. Furthermore, there are also up to 27 general purpose digital inputs or outputs if no other digital interfaces are used.

The microcontroller has 32 KB of program flash memory, which is enough for most applications. There is also 8 KB of data flash memory for storing user parameters. The microcontroller performs up to 60 millions of instructions per second. In addition to traditional control applications, the instruction set supports digital signal processing applications. The 56F8323 can be programmed via JTAG (Joint Test Action Group) interface or, using a bootloader, via serial port or CAN.

The external components required by the microcontroller were placed on the microcontroller board, too. These include an 8 MHz ceramic resonator, a 3.3 V voltage regulator, a reset circuit and capacitors and inductors for filtering the supply voltage. The 56F8323 has an on-chip relaxation oscillator but an external resonator or crystal is usually more precise. The CAN interface was considered essential in every application so a CAN transceiver was placed on the board, too. JTAG connector was included for programming and debugging the microcontroller. For programming and data logging via serial port, an option for a dual RS-232 transceiver was designed. The transceiver circuits need a 5 V supply voltage. All the other components operate at 3.3 V which is regulated on the board from the 5 V supply voltage.

Because the suitable connectors depend on the application, there are only pin headers on the microcontroller board. The JTAG connector is a 2 x 4 pin header for a flat cable. All the other inputs, outputs, interfaces, supply voltage and grounds are connected to two 20 pin headers on the long sides of the board.

B. Attachment-specific Board

The excavator has no sensors at the moment, so there was no need for inputs in the attachment-specific board. The PVG 32 requires PWM between 0 and 12 V. The microcontroller board outputs PWM between 0 and 3.3 V and sources or sinks a maximum current of only 12 mA. Therefore, a buffer circuit is needed. The PVG 32 operates without an external low-pass filter if the PWM frequency is high enough. Therefore, the buffer should have a bandwidth of at least 1 kHz. The microcontroller supports considerably higher frequencies so the buffer should enable experimenting with higher frequencies, too. An IPS024G MOSFET switch was selected. It accepts logic level inputs so connection to the microcontroller is easy: Only pull-up resistors to 5 V are required. The bandwidth depends on load. In this case it is hundreds of kHz. The IPS024G has four FETs in one package so only one component is needed. Furthermore, the IPS024G has internal protection against over-current, over-temperature, electrostatic discharge, and inductive loads. Since the IPS024G is a low side switch, pull-up resistors to 12 V are needed at the outputs. [7]

In addition, a 5 V voltage regulator was included in the attachment-specific board because the microcontroller board requires a regulated 5 V supply voltage. Some filtering capacitors were added because the battery voltage usually has some interference.

Screw terminals were selected for the wires. The battery voltage and CAN were wired to two-pole terminals and the valve outputs had three-pole terminals. The connections are shown in Table I. For the pin headers of the microcontroller board, corresponding sockets were installed.

TABLE I
CONNECTIONS TO THE EXCAVATOR MODULE

Cable	Wires	Connector
Power	+12 V Ground	2-pole screw terminal
CAN	CAN_L CAN_H	2-pole screw terminal
Valve outputs 1-4	+12 V PWM Ground	3-pole screw terminal

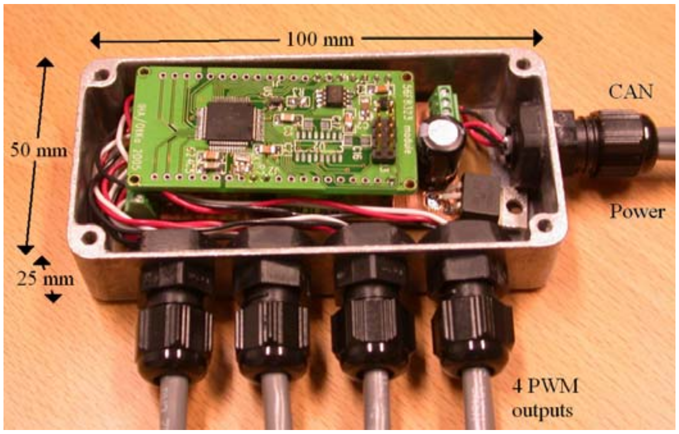

Fig. 4. The excavator module.

An IP65-classified case and cable glands were chosen. The cables were connected to the attachment-specific board. The board was mounted to the case by screwing the voltage regulator to the bottom of the case. This helps to cool the regulator which is the only component that generates considerable amounts of heat. Thanks to improved cooling, the same electronic unit is compatible with 24 V valves, too. A photograph of the excavator module without cover is in Fig. 4. The cables and the dimensions of the case are marked on the photograph.

IV. Software

A. Excavator Module

Software development tools for the microcontroller are easy to use. A C compiler with Processor Expert code generator is included as well as programming and debugging tools. The tools are also inexpensive, especially for academic use.

The present version of the software is merely a CAN interface for the valves. The program flow chart is presented in Fig. 5. When the interface unit is started, the microcontroller initializes the PWM outputs to 50 % duty cycle at 2 kHz. The FlexCAN is initialized to operate at 125 kb/s and to perform an interrupt when a message is received. The main loop of the program is empty, as the software only waits for an interrupt from the FlexCAN.

The CAN receive interrupt handler checks the ID field if it matches the CANopen message type PDO2 (rx) for node ID 20. PDO messages are used because the data are continuous control data. The node IDs 10, 11, 12, and 13 are, or have been, used by the modules installed in the mobile machine. Therefore, some node IDs were reserved for future development of the mobile machine and the node IDs 20 and greater were selected for the attachments. If the message ID matches, the data bytes are read from the message buffer. There are 8 data bytes in the message, which is sufficient for transmitting four 16-bit values. The four read values are used to set the duty cycles of the PWM outputs.

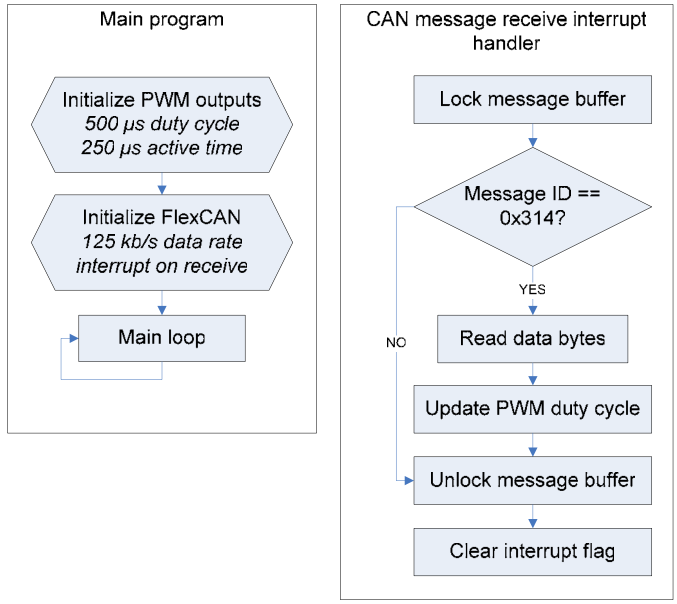

Fig. 5. The software flow chart of the excavator module.

B. Mobile Machine

The MVDM586 display module of the mobile machine is a PC compatible computer unit that controls the machine. It has a Linux operating system and the software is developed using a GNU C/C++ compiler. The computer sends CAN messages to MVMIO24 modules that control the valves of the machine.

When the excavator is operated, the machine should stay still. The program should therefore keep the valves that control hydraulic motors, the boom, and the bucket of the machine closed when the excavator is active. This frees the steering wheel and the joystick to control the excavator. On this ground, the software was modified by adding an excavator mode.

When a button on the display module is pressed, the computer toggles the excavator mode. When the excavator mode is on, the word “EXCAVATOR” is shown on the display. The display module stops sending CAN messages that control the boom, the bucket, the telescope, and the hydraulic motors of the mobile machine. The positions of the steering wheel and the joystick are still read but in the excavator mode they are used to control the excavator. The functions of the steering wheel and the joystick in the excavator mode are shown in Table II.

The position data from the steering wheel and the joystick are scaled to 16-bit values and sent in a PDO2 message with node ID 20, which is the node ID of the excavator module.

TABLE II
FUNCTIONS IN EXCAVATOR MODE

Input device	Controlled valve
Steering wheel	Near boom segment (lateral)
Scroller wheel on joystick	Middle boom segment
Joystick y-axis	Far boom segment
Joystick x-axis	Bucket

V. Test Arrangement And Results

The excavator module was mounted on the PVG 32 valve on the excavator. The four valve output cables were connected to the valve. The excavator was mounted on the mobile machine. The CAN and power cables were connected to the four-pole connector on the mobile machine. The excavator was lowered so that it was supporting the machine. The control system was then switched to the excavator mode.

The movements of all the cylinders were tested from the operator seat. The centre positions of the valves needed some adjustment to prevent the excavator from moving by itself. There were no disturbing delays or problems with the data transmission. Using the steering wheel to control the excavator requires some adaptation from the operator.

VI. Intelligent Functions

Although the excavator module was used mainly to act as an interface in this work, it is a flexible platform that is capable of performing complicated functions. The first steps to improve the performance could be dead zone compensation and ramp outputs. For safety reasons the module could close the valves after a set time from the last received CAN message. Parameters of these functions could be easily changed using CANopen SDO messages and stored in the data flash memory of the microcontroller.

Pressure sensors could be used to develop a load sensing excavator that would make simultaneous movements easier and smoother. Furthermore, the excavator could calculate the combined mass of the processed soil. Angle sensors would make bucket positioning possible. The CAN messages could include, for example, only depth and distance data and the excavator could operate automatically.

The microcontroller board is a sufficient platform for all the control algorithms required by these functions. Only small changes to the attachment-specific board are needed depending on the sensor types.

VII. Conclusion

The excavator module is compact, flexible and weatherproof. The electrical connection of the excavator consists of a single connector. No extra input devices such as joystick were needed. Furthermore, the module extends the teleoperation system of the mobile machine to concern the excavator. Two joysticks might be a better solution than the steering wheel to operate the excavator.

The 56F8323 microcontroller seems to be a good choice for this work. Different sensor and valve types are easy to connect, there is plenty of performance, and software development is quick. The module is easily configured to control almost any attachment. Intelligent functions can be effortlessly implemented.

Future research will include storage of valve parameters, load sensing, teleoperation applications, and different sensor-based smart functions.

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